NASA TECHNICAL NOTE

NASA TN D-3809

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JET SHOES - AN EXTRAVEHICULAR SPACE LOCOMOTION DEVICE

by David F. Thomas, Jr., John D. Bird, and Richard F. Hellbaum

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1967

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Technical Film Supplement L-892 available on request.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

This report presents the results of an investigation into the feasibility of an extravehicular locomotion device. This device consists of low thrust jets mounted on the soles of a pair of shoes to provide a controllable thrust vector which can be used to produce translational and rotational motions. It was found that with a little practice, the subject could control his attitude and motion with a reasonable degree of precision.

INTRODUCTION

With the increase in plans to use extravehicular activity in space operations, it becomes desirable that an extravehicular activity (EVA) propulsion device be designed that provides a high degree of mobility, is easy to use, and does not encumber the user so that he is unable to perform necessary tasks. This report presents the results of an investigation into the feasibility of one such device called "jet shoes."

The work of Charles Zimmerman and Paul Hill on the "Flying Platform" (refs. 1 and 2) demonstrated man's inherent ability to control a thrust vector pushing against the soles of his feet. It was found that the average person could maneuver the jet platform in translation by utilizing only his natural capabilities to maintain his balance. Considering this approach in conjunction with the fact that skin divers maneuver in a medium that simulates to some extent the "free fall" condition of space utilizing the small thrust developed by flippers attached to their feet suggests the concept of placing jets on the soles of the shoes of a subject in free fall. The more or less instinctive movement of the feet and legs to produce a desired motion may in this way be utilized to control the subject's rotary and translational motions.

Most of the testing done for this investigation utilized three-degree-of-freedom suspension systems wherein the subject was supported on his side in a horizontal plane. This arrangement provided him with one degree of rotational freedom (pitching) as well as fore-and-aft and head-to-foot translational freedoms. This limited simulation was believed to be sufficient for the preliminary nature of this investigation.

A motion-picture film supplement (L-892), which shows a series of tests using the various suspension systems and a number of the maneuvers, has been prepared and is available on loan. A request card and a description of the film are included at the back of this document.

JET SHOES EXTRAVEHICULAR ACTIVITY DEVICE

Figure 1 is a photograph of the extravehicular activity device investigated. This device may be thought of as a pair of shoes with jets attached to the shoe soles in such a manner as to produce a thrust vector approximately along the subject's leg when the jets are activated. A switch is mounted in the toe of the shoe so that a downward flexing of the toes closes the switch and thus turns on the jet. The jet on each shoe is independently controlled. It is recognized that this switching arrangement may not be adaptable for use with a full pressure suit. This method was used because it afforded a simple means of switching the jets on and off.

Preliminary tests with half-pound (2.228 newtons) thrust jets on the shoes indicated a need for more thrust to give the degree of maneuverability desired. Therefore a pair of $2\frac{1}{4}$-pound (10.008 newtons) thrust jets were installed and most of the testing was done with these jets.

It was found during the course of the test program that the jets should be mounted in order to provide forward pitching moment with the feet and legs in the position assumed when standing erect on a level surface. The reason for this bias stems from the fact that the knees do not bend forward and thus the forward pitching moment is limited to that which can be derived from ankle movement. On the other hand, backward pitching moment is readily obtained by bending the knees. The jets were mounted under the ball of the foot and tilted forward about 30° to achieve this result. This mounting produced approximately 8 foot-pounds (10.8464 joules) of forward pitching moment (using both $2\frac{1}{4}$-pound (10.008 newtons) jets).

No attempt has been made in this test program to arrive at an optimum configuration of the jet shoes. The intent was only to establish the feasibility of using this device for personnel self-locomotion in a zero-gravity environment. For this reason modifications were made to the original configuration only as the test program indicated the need of a change.

Criticism of some earlier models of the jet shoes arose because they were heavy, inconvenient to put on, and needed initial adjustment for convenient operation. Recently, a pair of shoes were constructed that are light in weight and extremely simple in design. These devices were constructed from a pair of aluminum roller skates and are readily attached to shoes or boots of any size by a spring system. These models of the jet shoes (figs. 1(c) and 1(d)) operate very well but they have not undergone extensive testing as yet and the results presented herein do not reflect this design improvement.

THE BALANCE PRINCIPLE

Reference 1 presents a thorough analysis of the balance principle as applied to standing on a fixed surface and as applied to standing on a thrust vector that is attached to and rotates with the feet. To aid in understanding the use of the jet shoes to provide a controlled motion at zero g, a brief description of this balance principle is provided here.

The application of thrust with the jet shoes produces a force vector acting through the center of gravity of the man when the feet are in the proper position. (See fig. 2(a).) The direction of motion will, of course, be headforemost. If an unwanted forward rotation is sensed, the natural reflex is to depress the ball of the foot which on a fixed surface produces a restoring moment which rotates the body backward into an upright position. With the thrust vector fixed to the feet, the result is to tilt the vector forward of the center of gravity as shown in figure 2(b); this movement produces a similar restoring moment. Forward restoring moment is obtained with the jet shoes by lifting the ball or fore portion of the foot while the jets are thrusting in much the same manner as the load on the ball of the foot is decreased to obtain forward pitching moment when standing. A significant factor in the use of the jet shoes is that the human sensory and psychomotor systems normally used in the everyday processes of balancing and orientation provide the necessary control judgment or feedback system that otherwise might have to be provided by an electronic system. Additional information on human balancing is available in reference 3.

TEST FACILITIES

Tests to determine the feasibility of the jet-shoe concept were performed on four different suspension arrangements. The four arrangements used were (1) a simple pendulum suspension, (2) a whipple-tree suspension, (3) a translating suspension system which was attached to the overhead dolly of the Langley rendezvous and docking simulator (see ref. 4), and (4) an air-bearing facility. Each system produced significant results and indicated the need for various modifications to the original jet-shoe configuration.

In the four arrangements, the zero-gravity simulation was accomplished by supporting the test subject on his side in a horizontal plane. It is readily apparent that the simple pendulum has the restriction of supplying only one degree of freedom (pitching rotation). This restriction is not an objectionable one when studying orientation capabilities. The other three arrangements had the rotational (pitching) degree of freedom as well as two translational degrees of freedom. This statement means that the subject could with these three suspension arrangements move in translation fore and aft and up and down as well as pitch forward or backward (with respect to his normal frame of reference).

The ratio of the rotational acceleration available on the whipple-tree system was high with respect to the available translational accelerations as a result of the large inertias introduced by the counter weights and beams that were a part of the whipple-tree system. (See fig. 3.) These counter weights had the effect of making the translations seem ponderous in relation to the pitching rotation. The test area available with the whipple-tree installation was a square 20 feet by 20 feet.

The translating suspension system did not have the limitations mentioned but did have a limitation on travel in one of the translational freedoms. This limitation effectively cut the testing area down to a 10-foot-wide (3.048 m) corridor which was then arbitrarily limited to a 40-foot (12.192 m) length. In addition, the quality of the zero-g simulation was strongly dependent on keeping the suspension cable vertical. A deflection of as little as 1 inch (2.54 cm) in 50 feet (15.24 m) caused a force error 0.4 pound (1.78 newtons) for the case of a subject weighing 225 pounds with his gear.

The scheme used to command proper motions of the carriage to keep the suspension cable vertical was as follows. (See fig. 4.) A closed-circuit television camera was mounted on the carriage at the top of the suspension cable. Appropriate acceleration levels were automatically put into the drive system of the carriage when the switches activating the jet shoes were closed. The longitudinal and lateral components of this acceleration were determined by monitoring visually the orientation of the subject through the closed-circuit television. Perfect correlation between the self-propelled motion of the test subject (using the jet shoes) and the commanded motion of the carriage resulted in a target point on the subject remaining at a fixed location on the television monitoring screen.

Plywood panels were set up on their edges to provide the test subject with reference surfaces within the confines of the whipple-tree and translating suspension test areas. With four panels, each 8 feet long, it was possible to simulate two opposing walls or a floor and adjacent wall. Portable fence posts such as are used to rope off areas in exhibition halls were used to mark starting points and target points in the various test runs on these two support rigs. When backed up by one of the plywood panels these posts represented handrails set out about 3 feet from a wall. The subject's task was to approach the target hand rail in such a manner as would permit him to come to a stop with his feet on the adjacent wall.

In the air-bearing facility, as used for this test program, the test subject was supported on his side on a cot. (See fig. 7 (a).) The legs were supported, for freedom of movement, by a boom and sling arrangement that was a part of the cot. The cot rested on three air-bearing pads arranged in a triangular pattern to provide stability. The bearing surface over which the pads moved was composed of a number of machined surface plates mounted to provide a highly accurate level floor.

TESTS AND RESULTS

Each of the four test rigs was utilized to determine the ability of the test subjects to control their motion when using jet shoes. In addition to this purpose, the various test rigs provided useful information on thrust level, jet location, and jet alinement.

Pendulum Suspension Tests

Preliminary tests using half-pound thrust jets in which the subject was suspended in a simple pendulum fashion indicated that the subject could maintain or change his orientation at will. With the half-pound thrust level, however, objectionably long time lags existed between initiation of a maneuver and the attainment of reasonable motion. For instance, it required nearly one complete rotation in forward pitch to attain a rate of rotation of 6 revolutions per minute. For this reason, a modification was made to provide approximately $2\frac{1}{4}$ pounds (10.008 newtons) of thrust from each jet. The $2\frac{1}{4}$-pound (10.008 newtons) thrust jets produced the faster reaction times that it was felt were required to permit the jet shoes to be used in a more or less instinctive manner.

Whipple-Tree Suspension Tests

The second series of tests were conducted with the subject suspended from a whipple-tree arrangement as shown diagrammatically in figure 3. Figure 5 shows a subject performing a translation and rotation task in which he accelerates away from one point, turns end for end, and brakes to a stop near the target point. This subject is inexperienced and introduces an unwanted pitching rotation at the start (figs. 5(b), 5(c), and 5(d)) and the trajectory is off the direct path. In figures 5(e), 5(f), and 5(g), it can be seen that the unwanted rotation has been brought under control but the trajectory is still off. Figures 5(h) to 5(k) show that a backward rotation was induced which brought the subject into proper orientation for arrival at the target and also brought the trajectory back to the target position. Runs such as this one showed that the jet shoes would give control in translation as well as in orientation.

At the point in the test program when the jet size was increased to $2\frac{1}{4}$ pounds (10.008 newtons), it became apparent that the jets should be mounted forward on the shoes and tilted with respect to the sole of the foot. It was found by trial and error that placing the jets under the ball of the foot and tilting them forward about 30° gave the proper "feel" when the jets were turned on. This combination of position and tilt of the jet permitted the pitching moment to be varied through a zero moment and into a backward moment by means of normal leg and foot motions.

Having obtained a reasonable amount of information from the tests conducted on the whipple-tree suspension system, it became apparent that for a more precise evaluation of the jet shoes, it would be necessary to use a test rig that did not degrade the translational motions of the subject because of the inertias of the test rig itself.

Translating Suspension Tests

The third series of tests were conducted on the suspension system in which the suspension cable was attached to an overhead carriage which could be translated longitudinally and laterally under its own power. The facility used for this series of tests was the Langley rendezvous and docking simulator.

In this series of tests one subject, with no experience in zero or reduced-gravity simulation previous to this program, found that combination translation and rotation tasks could be performed after practice. On the other hand, a test subject (also an engineer) having experience in reduced-gravity simulations (refs. 5 and 6) and, consequently, a well-developed coordination performed the same tasks and more intricate maneuvers with little or no practice. Figure 6 shows the latter test subject performing the task of leaving a point, moving out to a specified point, stopping, and heading back toward the starting point.

In a series of runs in which the ankles were immobilized, it was found that it was still possible to perform the translation and attitude tasks utilizing only knee and hip motions as long as some forward pitching moment was provided by the jet location and alinement. However, in the absence of a built-in forward pitching moment, it was impossible to maneuver satisfactorily.

During the latter stages of the third series of tests, the more experienced test subject expressed the opinion that for those tasks in which a series of maneuvers were required, it might be advantageous to operate at a lower thrust level. The jets were therefore regulated to produce approximately 1 pound (4.448 newtons) of thrust each. This thrust level in no way hampered the performance of the simpler maneuvers; in fact, it increased the ease with which the simple maneuvers were performed.

Air-Bearing Facility Tests

A fourth series of tests were run on the Manned Space Flight Center's air-bearing facility. This facility provided a nearly frictionless zero-g simulation in which the test subject was free of problems resulting from support system mass or external powering of the support system.

Figure 7 is a series of photographs showing a test subject on the air-bearing facility moving outward from a target, performing a forward flip, and coming back into the target. This task was executed successfully the first time the test subject tried it.

Two points of interest became evident during this fourth series of tests: first, the subjects tended to perform the assigned tasks in a more deliberate manner (that is, the translational and rotational velocities were slower) and, second, little improvement in performance of a task resulted from attempts to plan ahead of time when, where, and how much control to put in. This latter point would appear to emphasize the instinctive use of the jet shoes.

Switching and Mounting Considerations

It is recognized that the jet-actuation arrangement used in this study may not be adaptable for use with a full pressure suit. The same would, in all probability, be true for the mounting. Some approaches to the actuation and mounting problems that came to mind during the course of this investigation are mentioned here for information.

Two novel approaches to the jet-actuation problem in conjunction with a space suit were considered. These schemes were devised to maintain the integrity of space suits as presently designed.

The first approach would use electrical components and inertia switches mounted on the exterior of the shoes or lower legs of the pressure suit. In using this system the subject would kick his feet as in swimming to activate the jets. Each kick of the foot would produce a short burst from the jet. A rapid series of kicks would result in an almost continuous thrust.

The second approach would utilize a small portion of the air that is normally used for cooling to operate a pneumatic logic that would include a valve turned on or off by the toes and possibly pneumatic amplifiers to arrive at the power level required to open the jets.

As for the mounting arrangement for the jets, it is quite possible that a fixed mounting would not be optimum because of the restrictions imposed on foot and leg movements by the full pressure space suit. In that case a more desirable arrangement might be a mounting that would amplify ankle, knee, and hip movements to swivel the jets to provide the desired control moments. This augmented mounting opens the way for a more efficient utilization of thrust in that the control moment bias may take the form of an augmentation bias rather than a position bias in the form of a forward tilt of the jets under the foot. That is, ankle movements intended to produce forward pitching moments may be amplified more than ankle movements for backward pitching moments.

CONCLUDING REMARKS

The simulations made in this investigation have shown that a simple low-thrust jet arrangement composed of a pair of jets, one suitably mounted on each shoe has considerable potential for use in extravehicular locomotion in space. These jet shoes enabled the performance of translation and orientation maneuvers in three degrees of freedom in a plane parallel to the surface of the earth with ease. Additional tests of the jet-shoe concept should be made under conditions that permit full six-degree-of-freedom motion such as in zero-g aircraft flights and in orbital space flights.

These tests showed that thrusters of 1 to 2 pounds each provided a reasonable feel for attitude and translational control, and that a satisfactory position of the jets was under the ball of the subject's foot. It was found that the jets should be pointed forward approximately 30° from the vertical to the sole of the shoe to provide about equal forward and backward pitching moments from the jets. It was possible to perform translation and attitude control tasks with the ankles immobilized by utilizing knee and hip motion as long as the jets were pointed somewhat forward under the foot.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 23, 1966,
749-51-05-01-23.

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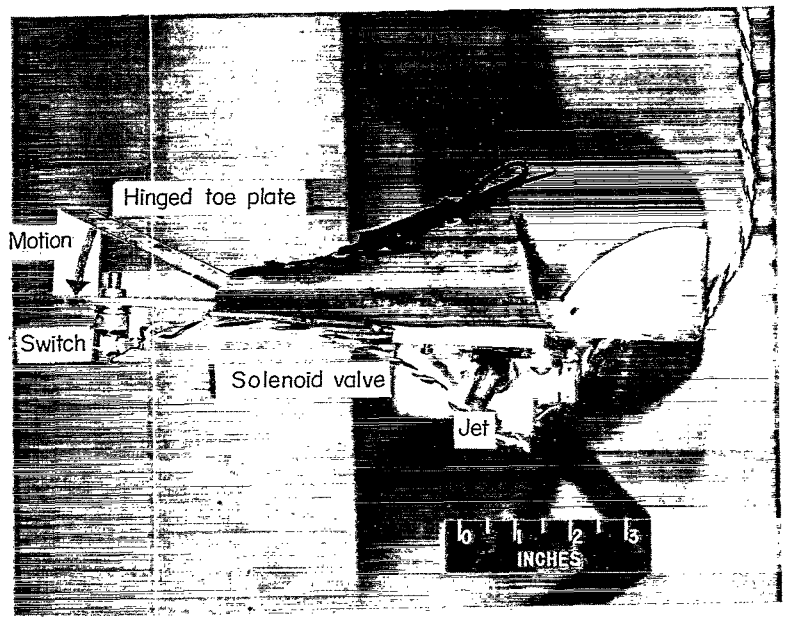
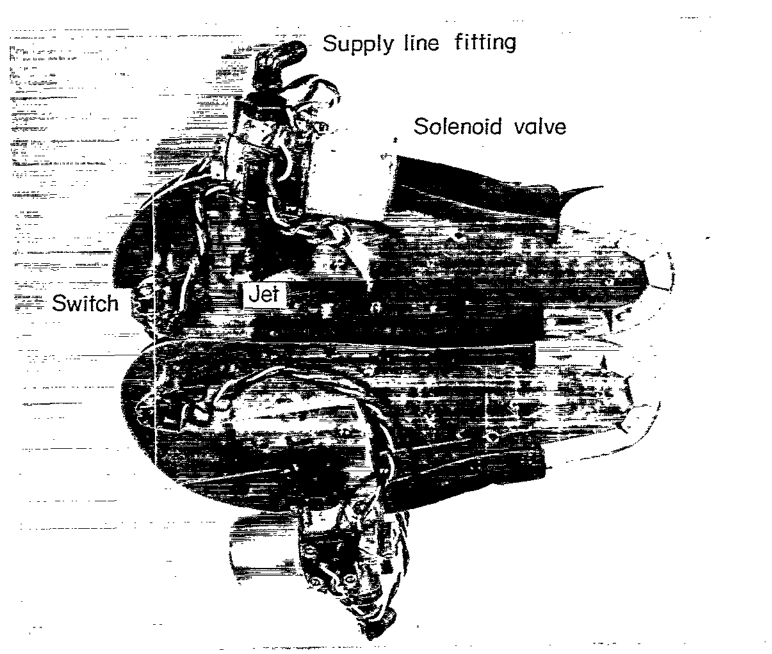


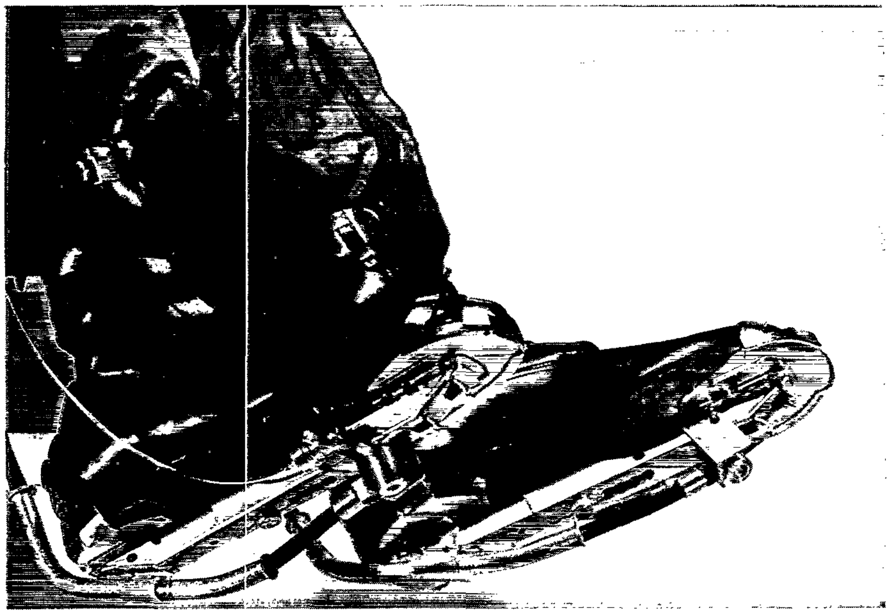
(a) Jet under instep of foot.



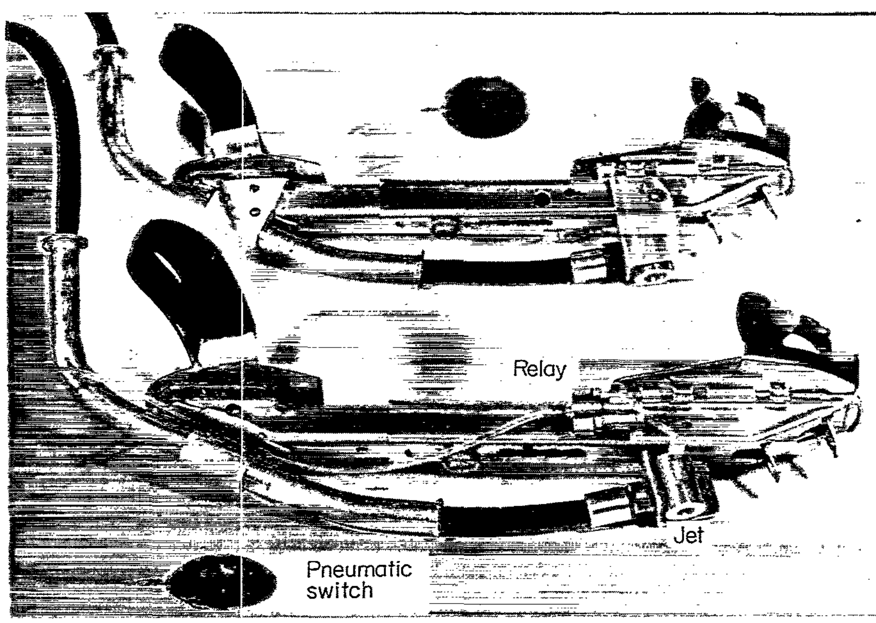
(b) Jet under ball of foot.

L-66-7654.1

Figure 1.- Jet shoes, an extravehicular locomotion device.



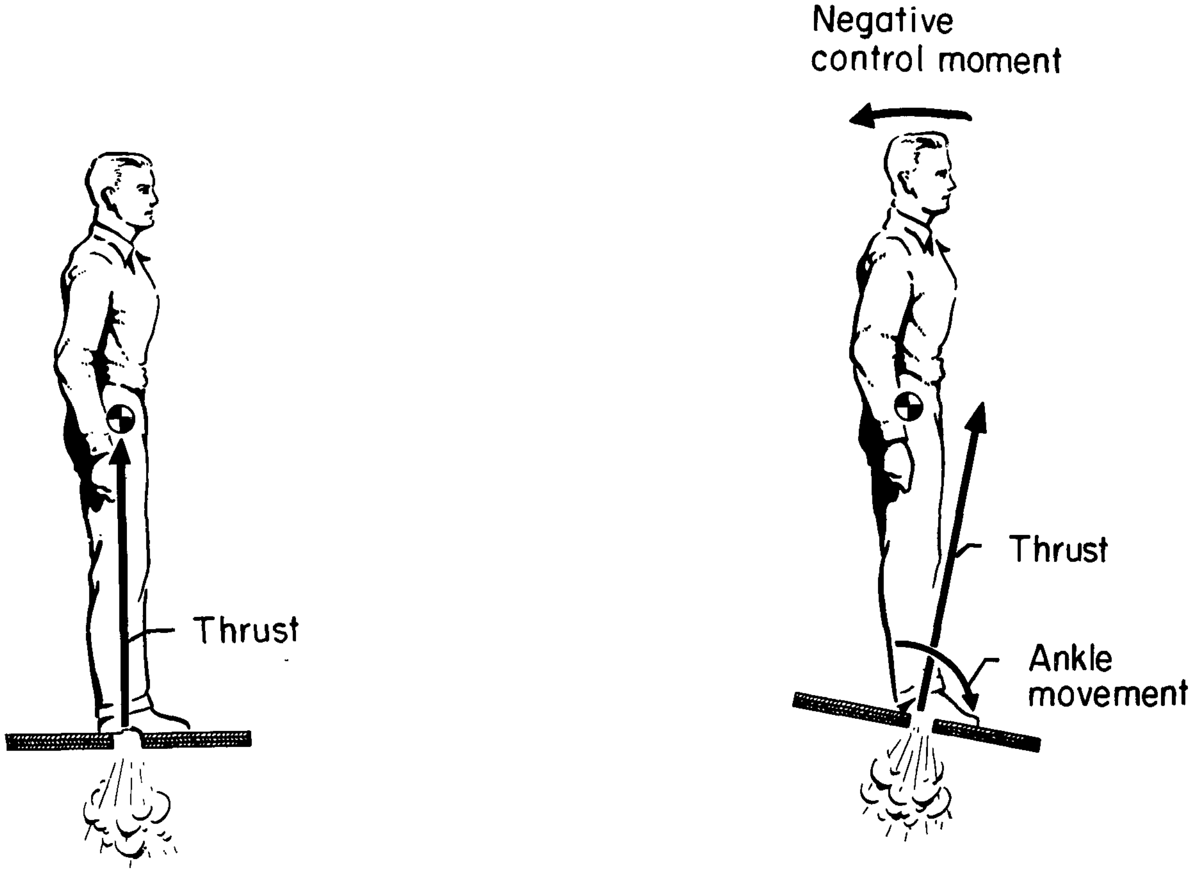
(c) Subject wearing jet shoes.



(d) Modified jet shoes.

L-66-7655

Figure 1.- Concluded.



(a) Translation only
no rotational control

(b) Rotational control

Figure 2.- Force and control moments resulting from rotation of ankles.

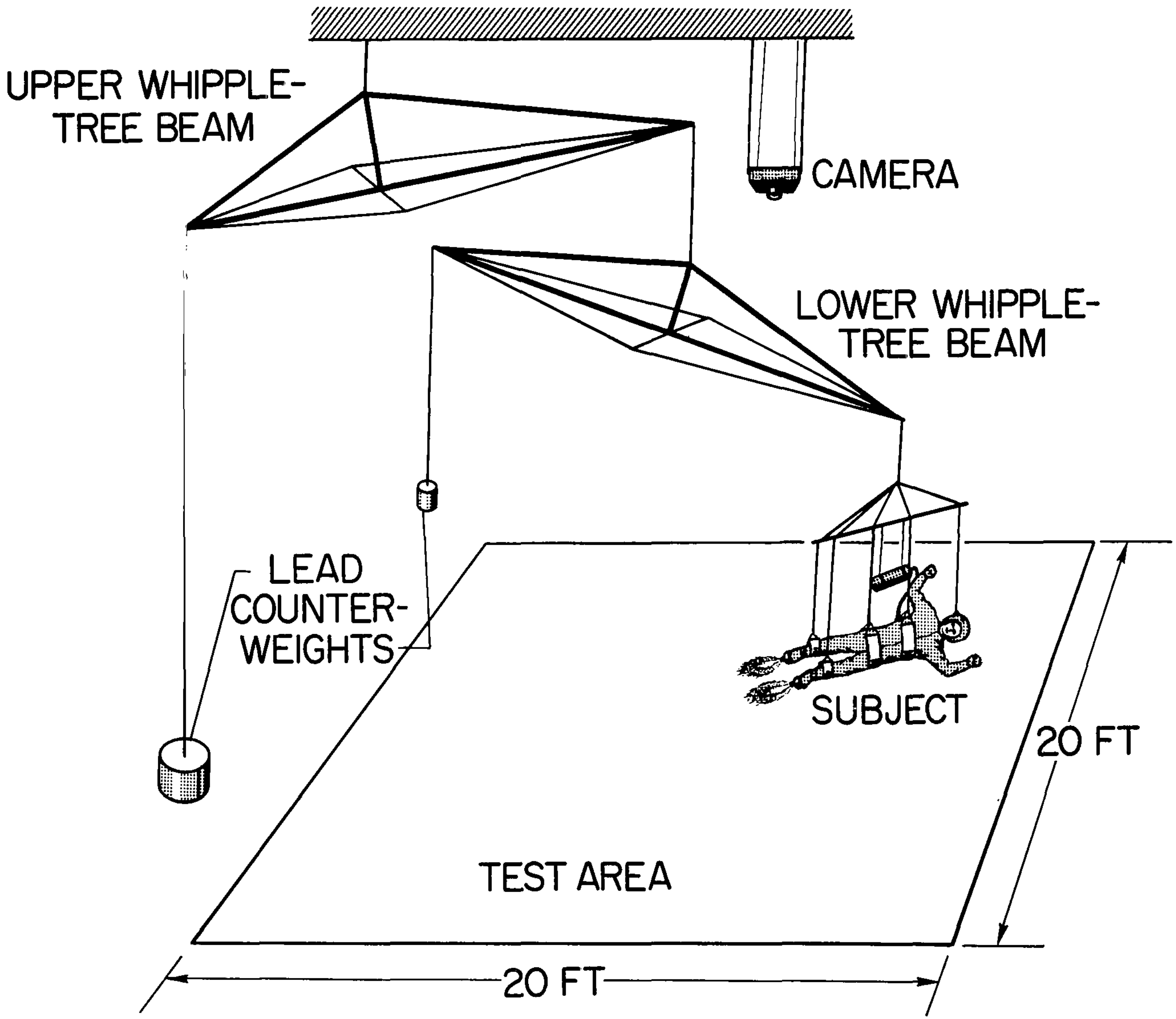


Figure 3.- Schematic of whipple-tree suspension system.

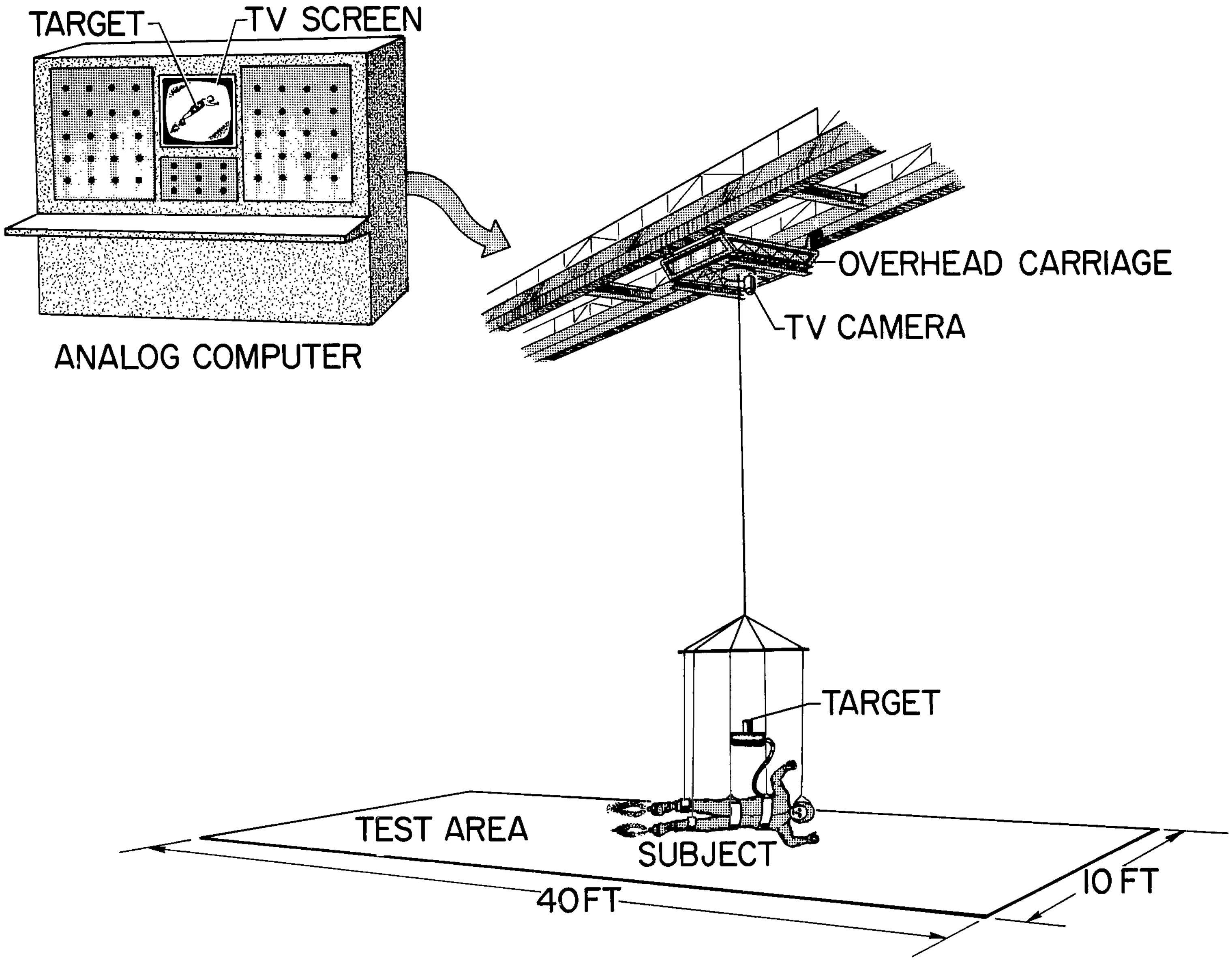
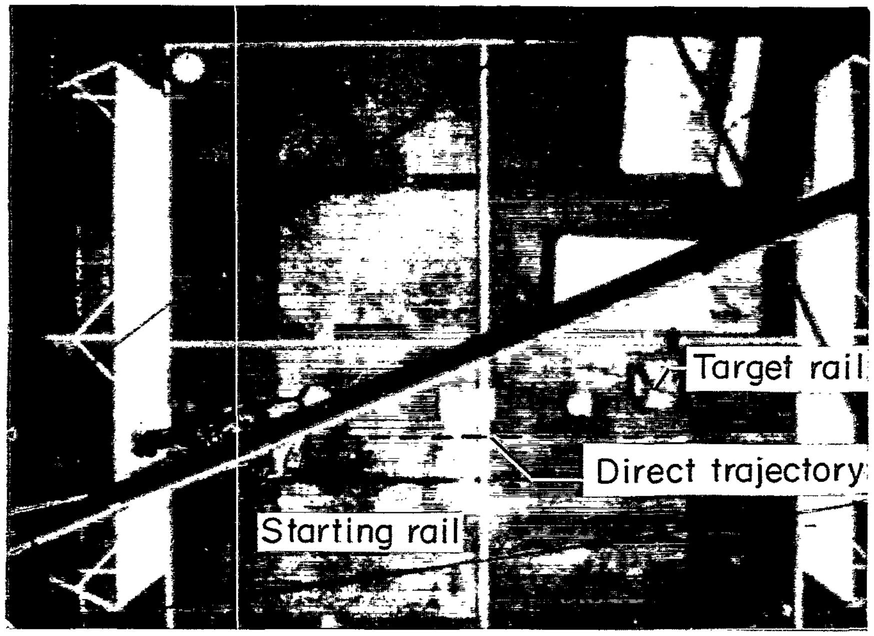


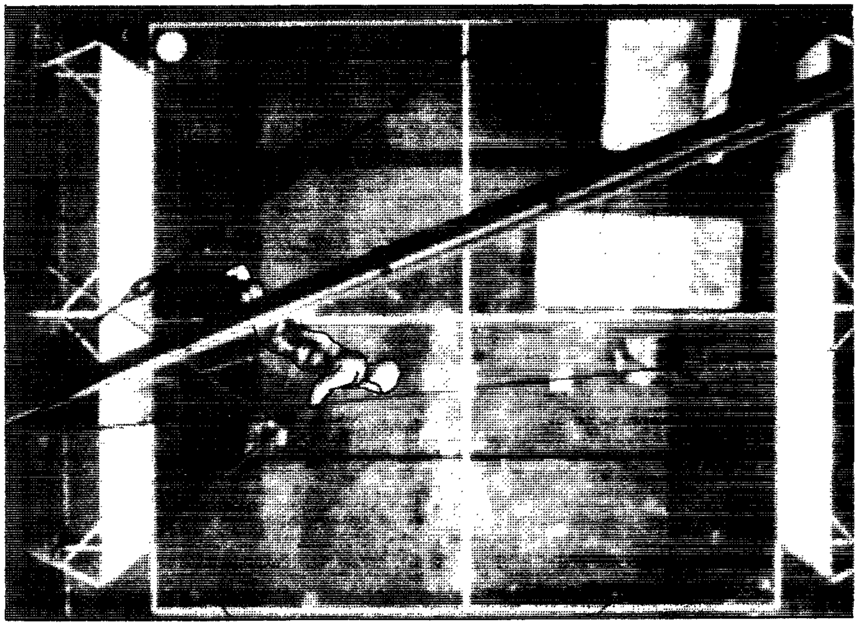
Figure 4.- Schematic of translating pendulum suspension system.



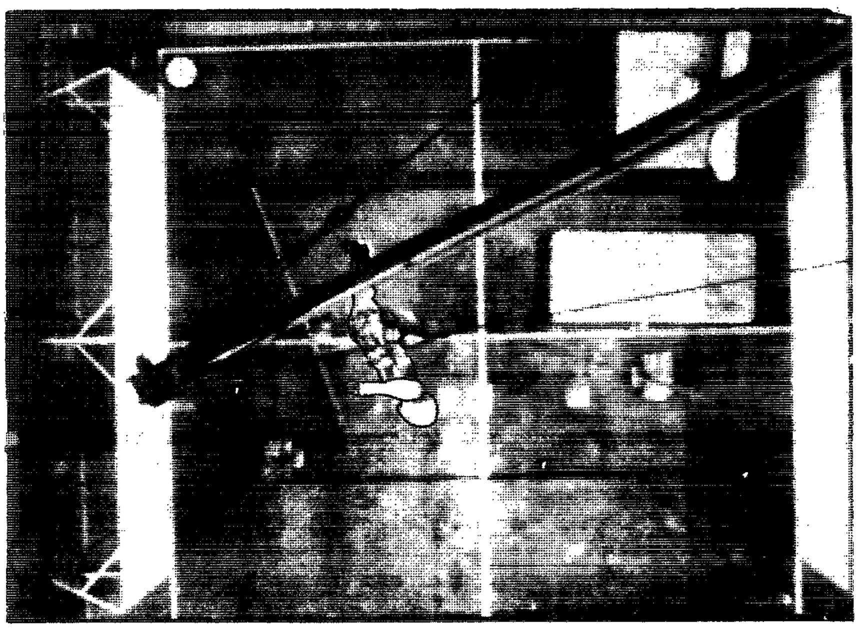
(a) Starting position; feet on wall and hands on bar.

(b) Position at end of initial thrust. L-66-7637.1

Figure 5.- Point-to-point translation with midcourse rotation and feet-first landing. Whipple-tree suspension.

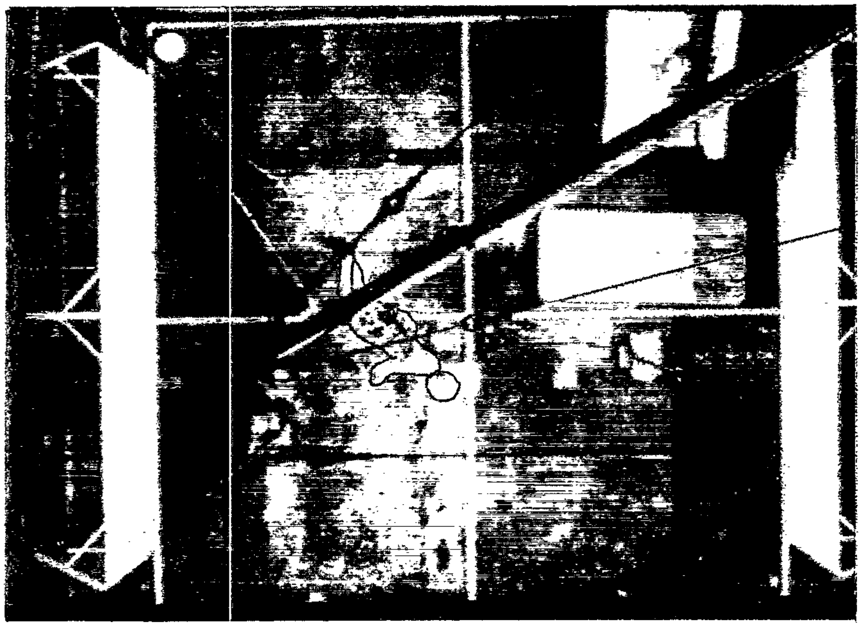


(c) Coasting with face-down pitching rotation.



(d) Still coasting; trajectory too high to hit target. L-66-7638.1

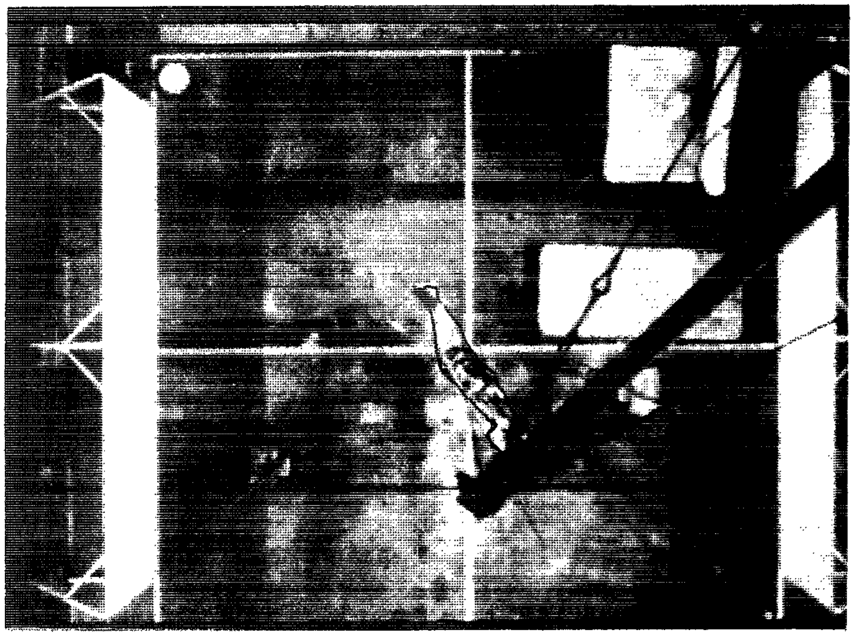
Figure 5.- Continued.



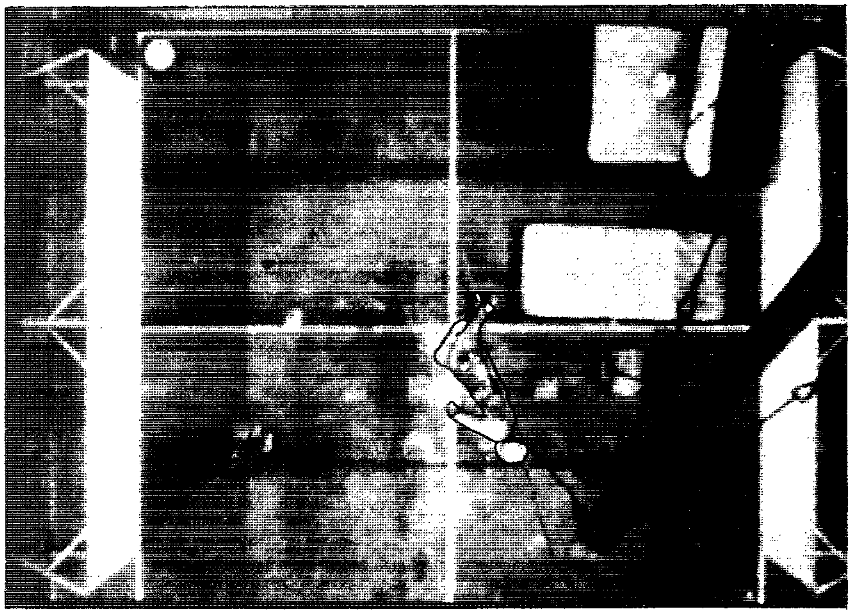
(e) Control input to stop face-down rotation.

(f) Midcourse thrust toward target. L-66-7639.1

Figure 5.- Continued.

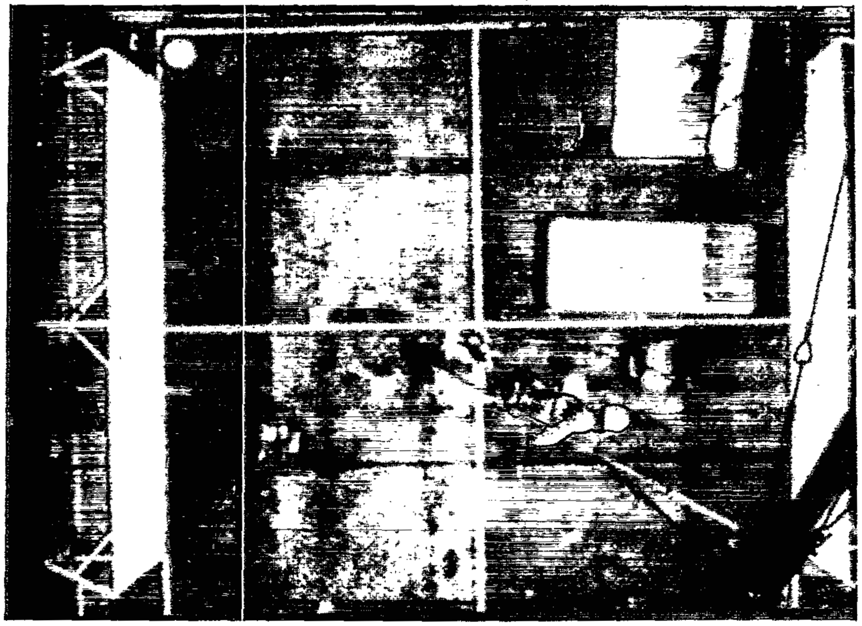


(g) Face-down rotation induced by midcourse thrust.

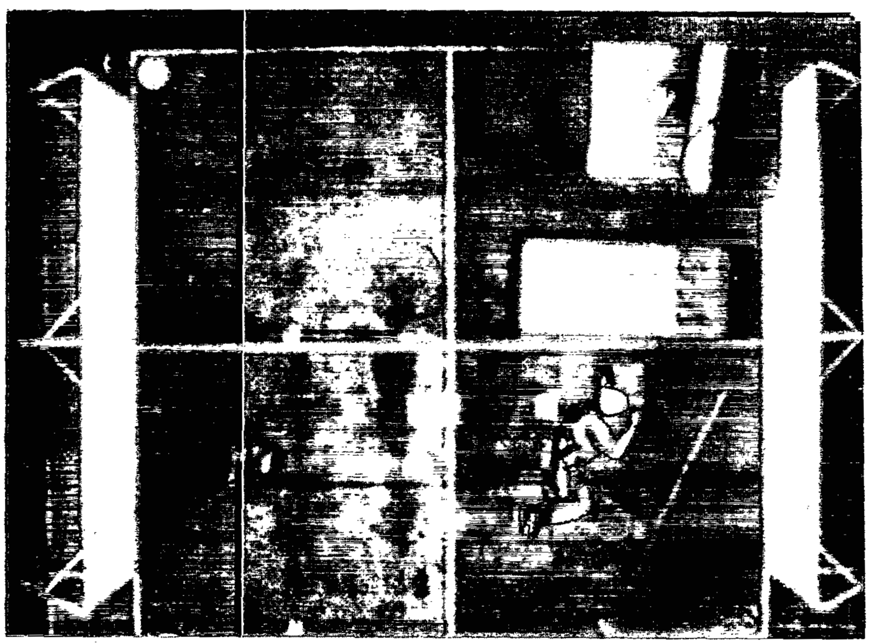


(h) Head-backward and trajectory lowering control input. L-66-7640.1

Figure 5.- Continued.

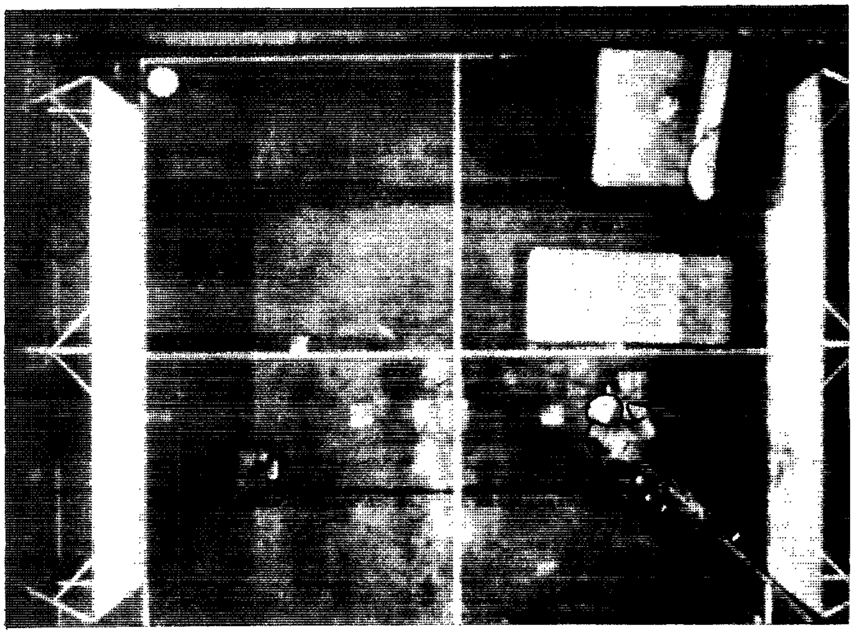


(i) Trajectory below target and head-backward rotation continuing.

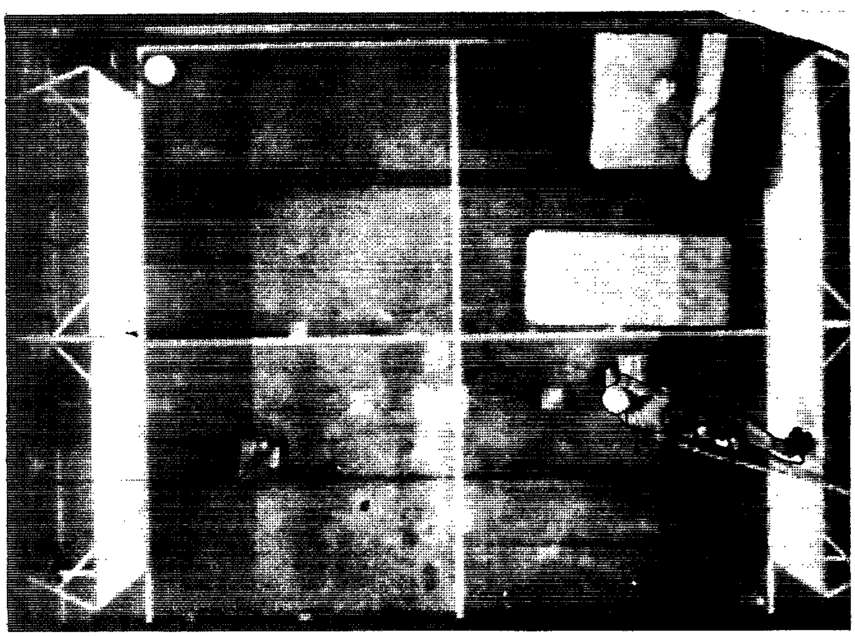


(j) Trajectory coming up to target and head-backward rotation continuing. L-66-7641.1

Figure 5.- Continued.



(k) Arrival; hands on bar and thrusting to stop rotation and translation.



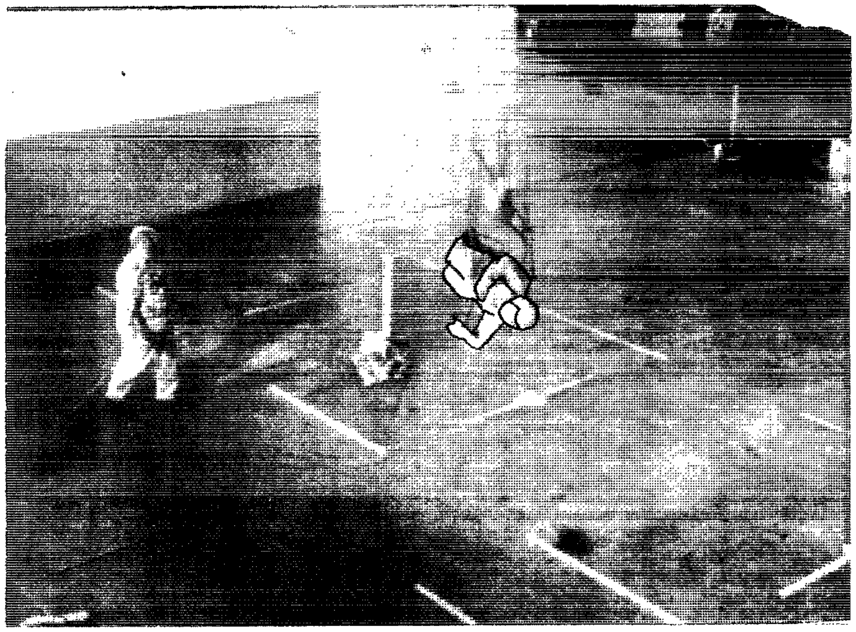
(l) Final position; feet on wall and hands on bar. L-66-7642.1

Figure 5.- Concluded.

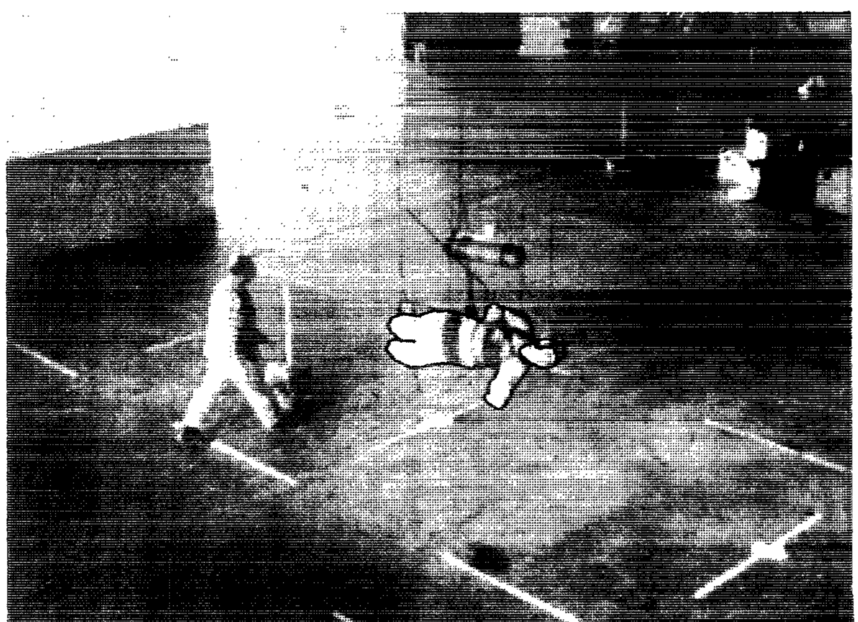
(a) Starting position; hand on pylon.

(b) Initial translation thrust. L-66-7643.1

Figure 6.- Translation with reversal of direction of travel maneuver. Translating pendulum suspension.



(c) Legs bent to input head-backward rotation.



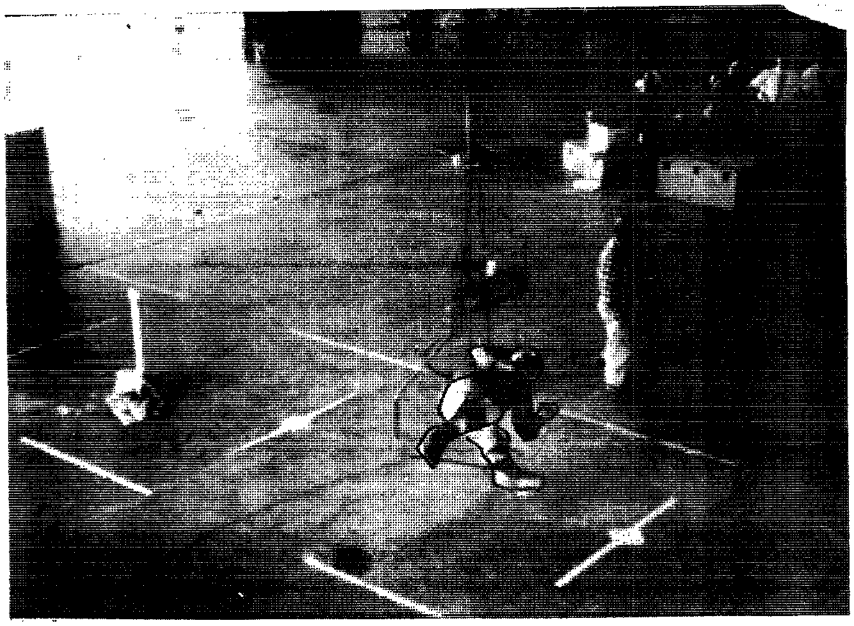
(d) Head-backward rotation started. L-66-7644.1

Figure 6.- Continued.

(e) Coast in translation and rotation.

(f) Lateral translation corrective thrust input. L-66-7645.1

Figure 6.- Continued.



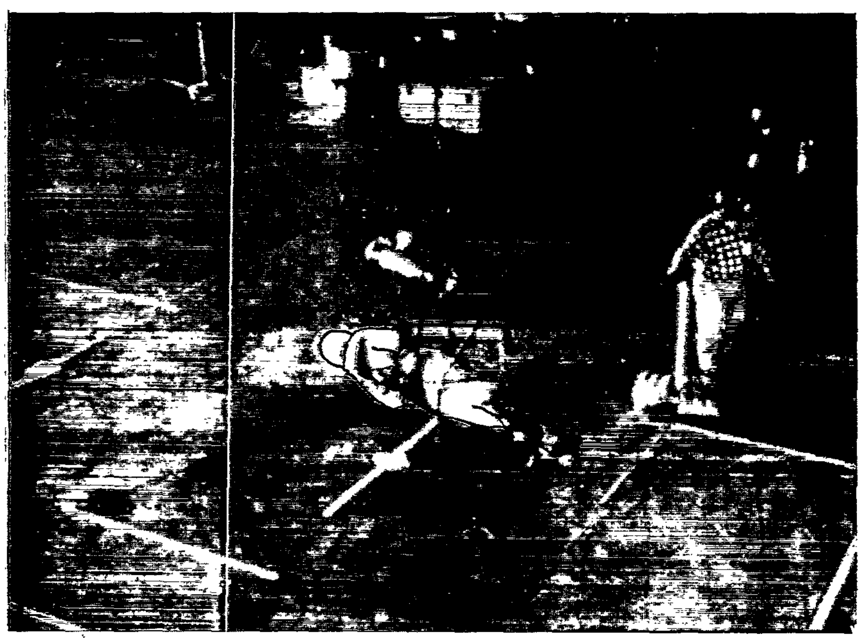
(g) Legs being swung forward for braking maneuver.

(h) Braking thrust started.

L-66-7646.1

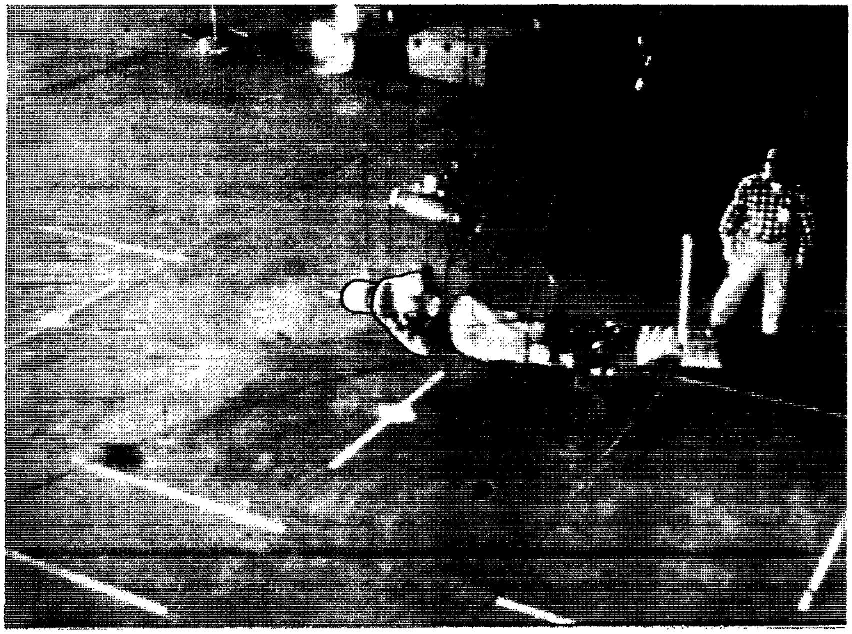
Figure 6.- Continued.

(i) Braking continued.

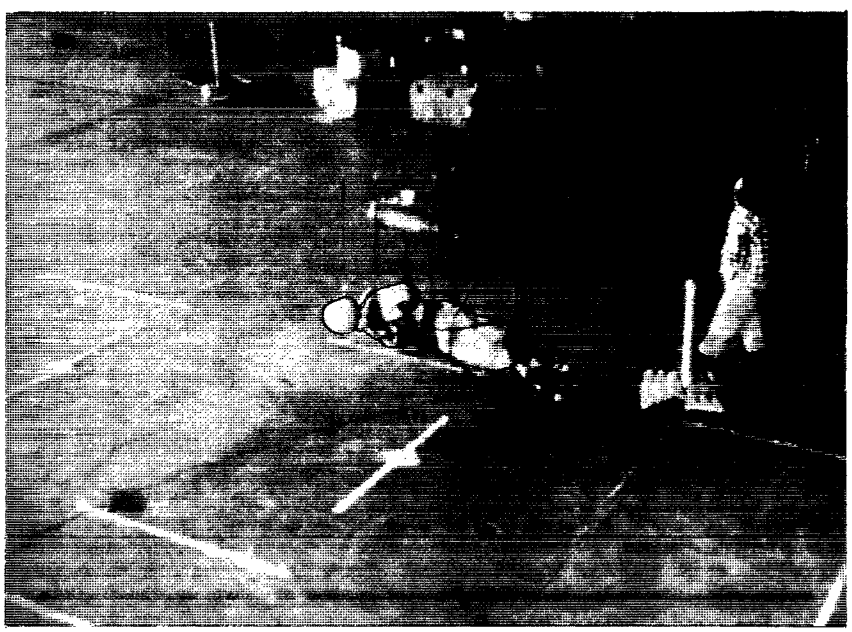


(j) Full stop and alinement for return achieved. L-66-7647.1

Figure 6.- Continued.



(k) Thrust initiated for return.



(l) Return to starting point underway.

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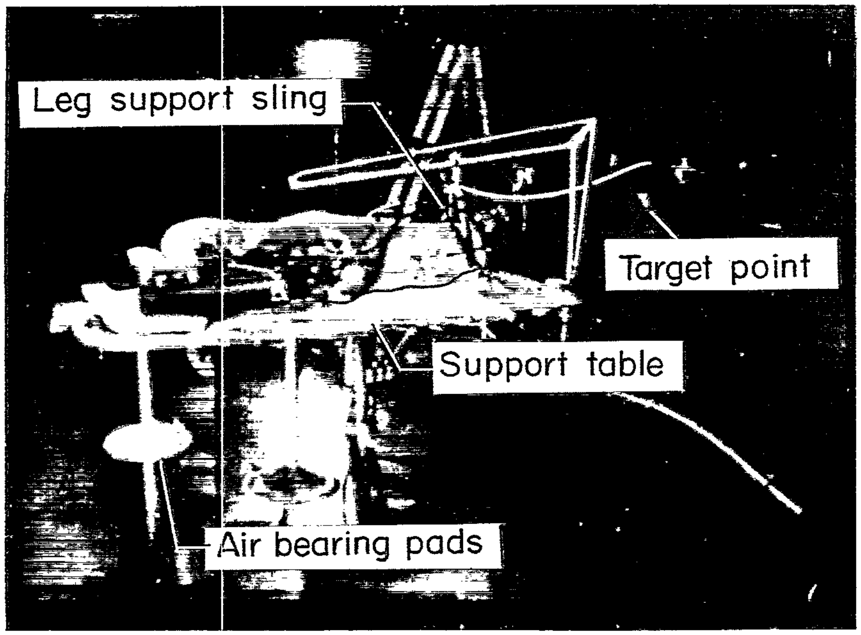
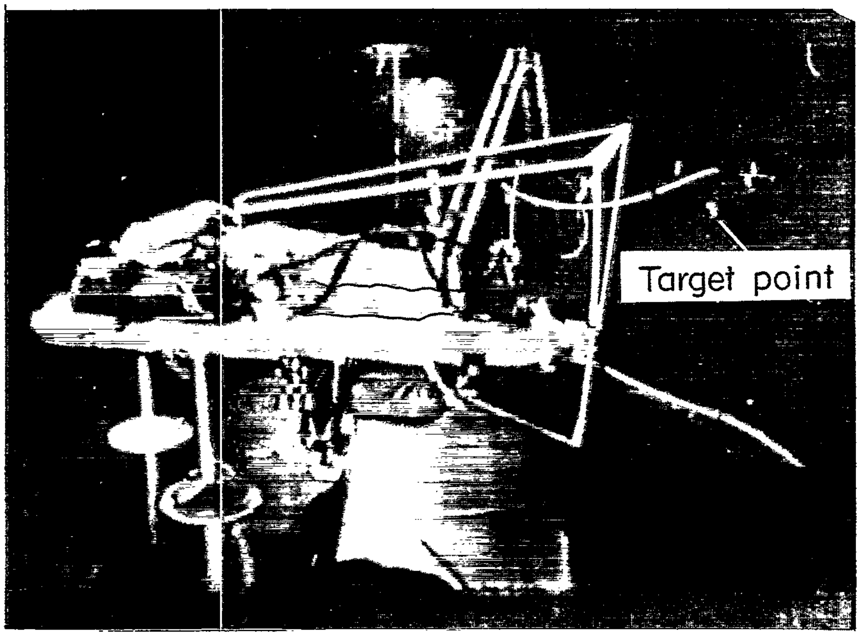
Figure 6.- Concluded.

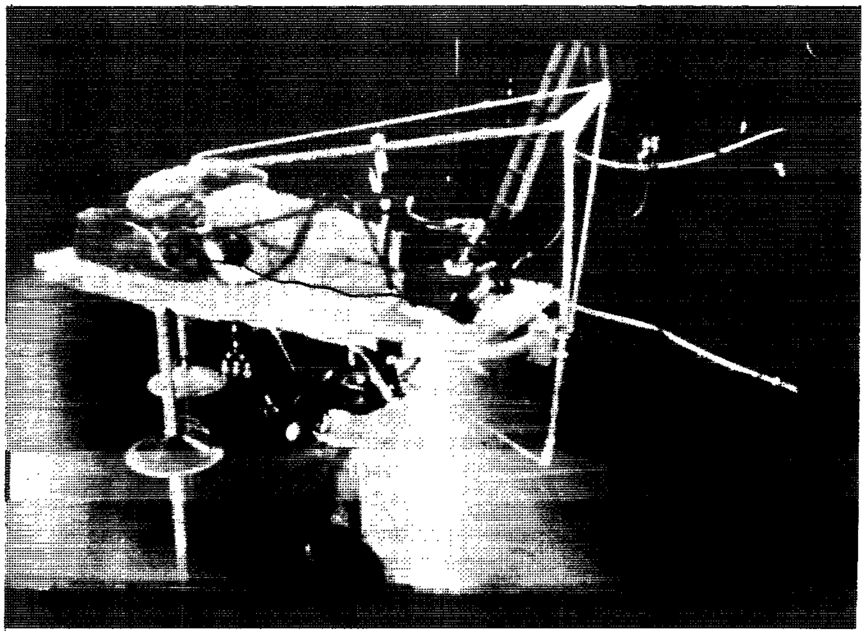


(a) Starting position, feet pointed toward target.

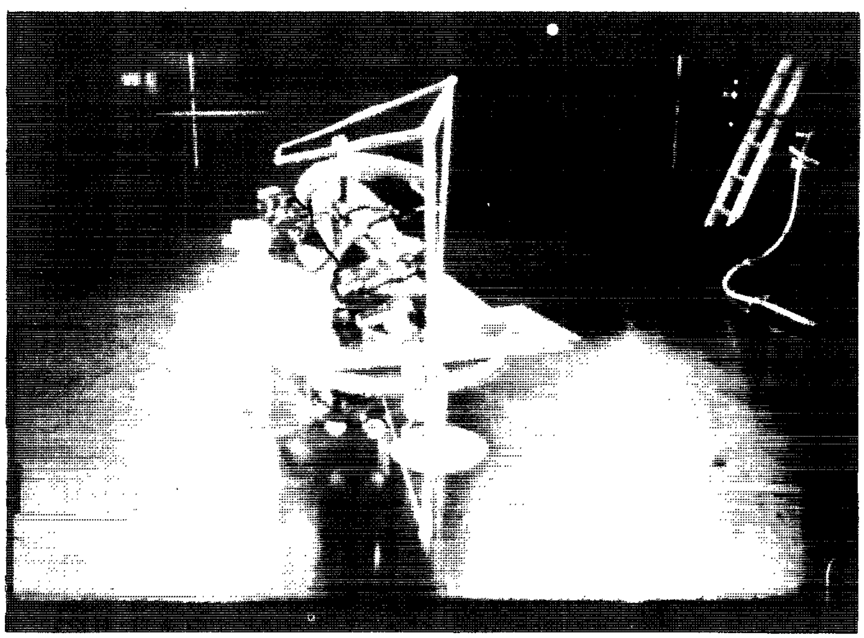


(b) Outward translation with forward rotation. L-66-7649.1

Figure 7.- Out and back with forward flip on air-bearing facility.

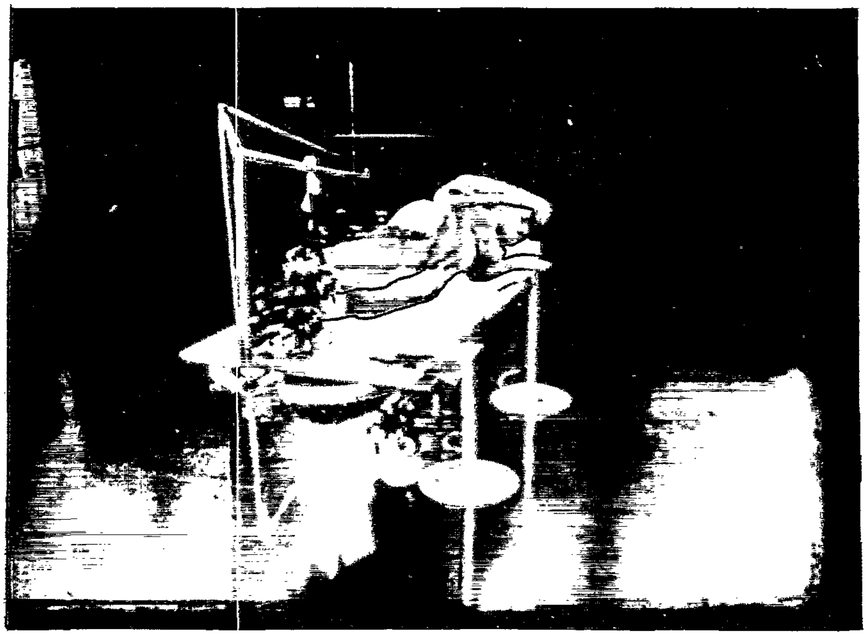


(c) Lateral component of translation stopped.

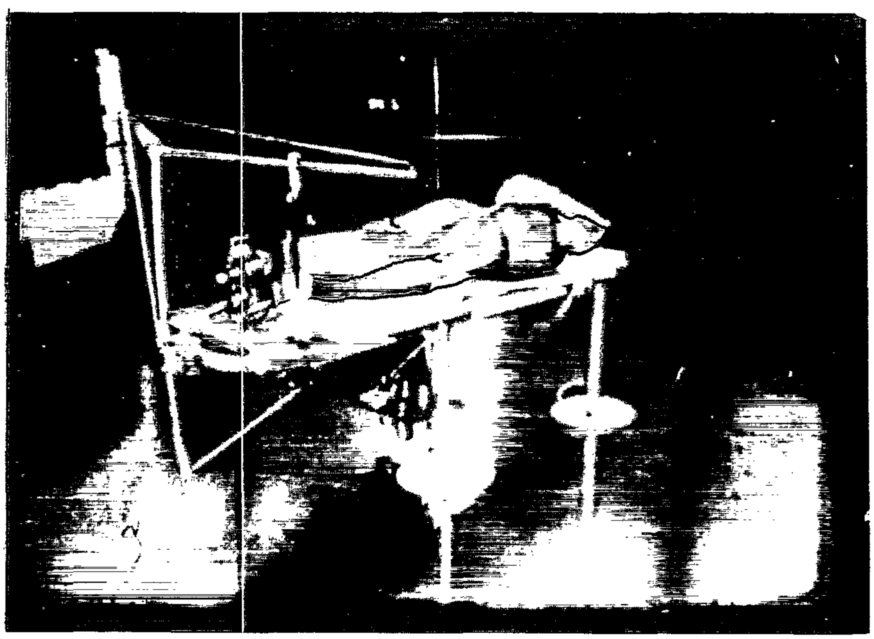


(d) Rotation half completed. L-66-7650.1

Figure 7.- Continued.



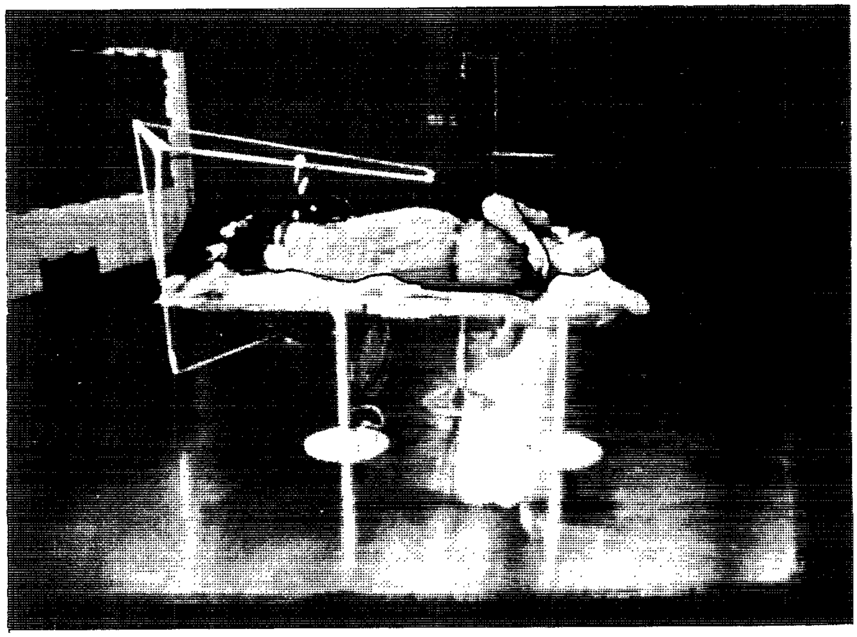
(e) Rotational and translational coasting.



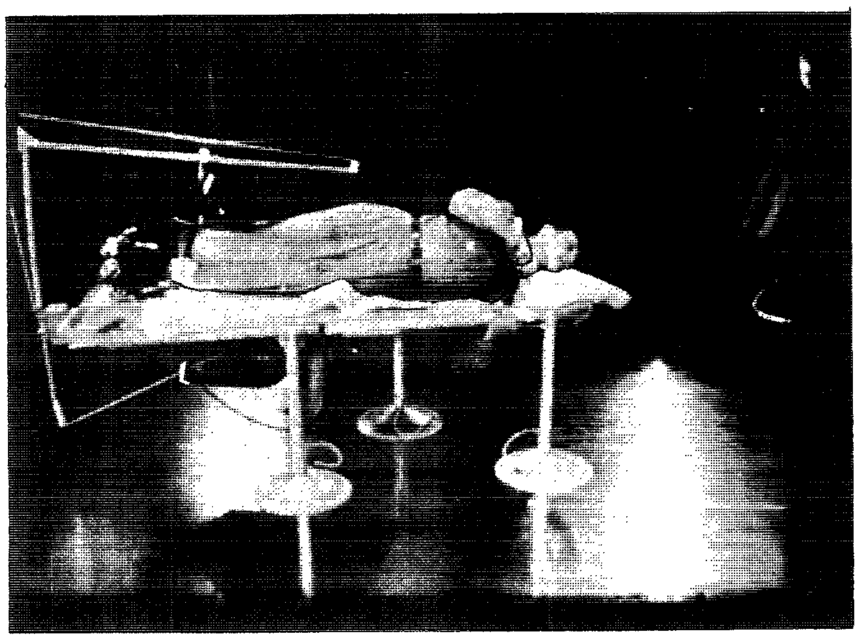
(f) Start braking the outward translation.

L-66-7651.1

Figure 7.- Continued.



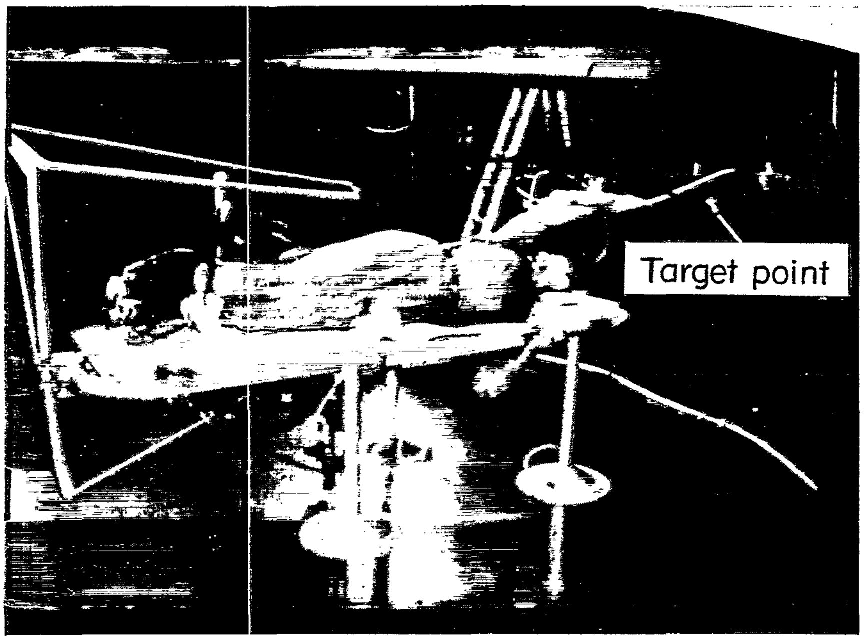
(g) All translations and rotations stopped; alined with target.



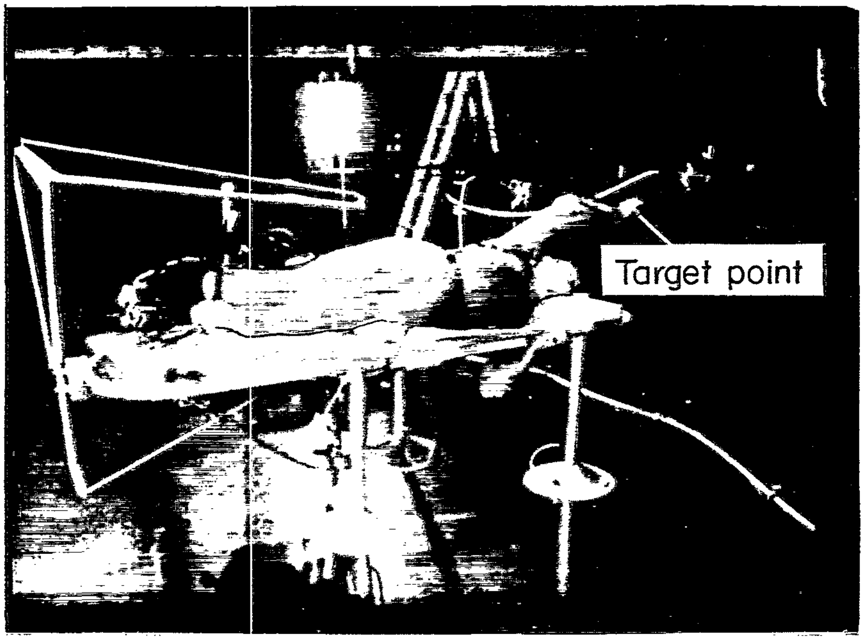
(h) Translation back toward target initiated.

L-66-7652.1

Figure 7.- Continued.



(i) Closing on target with no unwanted translations or rotations.



(j) Final position at target, feet pointed away from target.

L-66-7653.1

Figure 7.- Concluded.

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