DESIGN AND TEST OF A FULL-SCALE, WEARABLE, EXOSKELETAL STRUCTURE

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FOREWORD

This report describes the work performed by the Cornell Aeronautical Laboratory under Contract No. Nonr-3830(00), sponsored by the Office of Naval Research of the Department of the Navy. The time period covered is from 16 February 1963 to 15 March 1964. The program was conducted under the direction of Dr. Gilbert C. Tolhurst and Dr. James W. Miller, Psychological Sciences Division, Office of Naval Research.

ABSTRACT

A final design of a nonpowered, wearable exoskeletal device is presented. The device follows all basic movements of the wearer except for the fingers, toes and neck. Two features of the exoskeleton are that each joint has adjustable stops that can be used to limit the range of motion, and each joint is instrumented to record its position continuously with time. The exoskeleton is adjustable for size so that it can be worn by 90 percent of the adult, male population. (The source of the anthropological data used is presented in Reference 1.)

A test program is discussed that is used to draw conclusions concerning the feasibility of surrounding a person with an exoskeleton during the performance of work tasks. Experiments to determine experimentally the effect of limiting the allowable range of motion at given joints upon the ability of the subject to perform selected tasks are presented. Velocity and acceleration of exoskeletal joints during the performance of certain tasks are given.

ACKNOWLEDGEMENTS

This report is approved by:
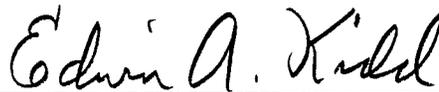
Edwin A. Kidd

Edwin A. Kidd
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1. INTRODUCTION

The Man Amplifier, as conceived by Cornell Aeronautical Laboratory, Inc., (CAL), is an exoskeleton, employing powered joints, that is worn by a man to augment and amplify his muscular strength and to increase his endurance in the performance of tasks requiring large amounts of physical exertion.

In the developed concept, the Man Amplifier would consist of a structural exoskeleton with appropriate articulated joints, compatible with those of man. All external loads, as well as the weight of the Man Amplifier itself, are borne by this structural skeleton. Each joint is powered by one or more servomotors which provide the necessary torques and power boost. These servomotors (1) respond to the outputs of sensors linking man and machine and (2) cause the appropriate mechanism to follow the natural motion of its human counterpart. In the original concept, a portable, self-contained power pack is attached to the back of the exoskeleton to provide the necessary power.

Preliminary investigations of the Man Amplifier concept (Reference 5) consisted of (1) analytical studies to define some of the major problem areas which must be examined in detail before the technical feasibility of the concept can be established, and (2) experiments, using the CAL elbow-joint amplifier, to obtain a preliminary indication of man-machine compatibility.

It was concluded that: (1) duplication, in the Man Amplifier, of all the human motion capability would be impractical, (2) experimentation would be necessary to determine the essential joints, motion ranges and dynamic responses, (3) the inability to counter the overturning moments would, in some instances, limit the load-handling capability of a single Man Amplifier, (4) conventional valve-controlled hydraulic servos are unsuitable for the Man Amplifier as regards efficient use of power, and (5) particularly difficult problems will be encountered in the general areas of mechanical design, sensors and servomechanisms.

CAL subsequently conducted (References 1 and 2), during a previous program, an investigation to generate a preliminary design for a nonpowered exoskeletal structure. Three basic exoskeletal joints were devised that, when combined, permit essential body movements of the wearer. Dimensions of the human body, pertinent to the design, and ranges of dimensions required to include 90% of the adult, male population were presented.

CAL has conducted, during the present program, an experimental investigation of the compatibility existing between a human occupant and an exoskeletal structure possessing limited joint degrees of freedom. An exoskeleton was fabricated and tested that contained 38 pinned joints and one sliding joint. An experimental investigation was conducted to determine the minimal number of joints (and their location) that must be provided in an exoskeletal structure, in order that the wearer can perform certain tasks.

Section 2 of this report presents the design of the exoskeleton used. The manner in which the preliminary design (References 1 and 2) was altered is discussed, and physical properties of the exoskeleton are given.

Section 3 presents tests conducted with the exoskeleton. The tests are divided into two groups: (1) tests concerned with the lower extremity (hip, knee, ankle and foot), and (2) tests concerned with the upper extremity (shoulder, elbow and wrist). The effect of limiting the allowable range of joint motion at various lower extremity joints is presented. The displacement, velocity and acceleration of exoskeletal joints during the performance of certain tasks are presented.

Conclusions that were formed from the experimental program are presented in Section 4.

2. DESIGN OF THE EXOSKELETAL STRUCTURE

Pictures of the exoskeleton produced during this program are shown in Figures 1, 2 and 3. The exoskeleton shown was designed by combining three basic joints plus one sliding joint in the manner discussed in References 1 and 2. The exoskeleton has mechanical stops at each joint that can be used to limit the allowable range of motion. Distances between the exoskeletal joints are adjustable so that the device can be made to fit 90 percent of the adult, male population. Each joint, with the exception of the sliding joint, is able to be instrumented to record its angular position as a function of time. The sliding joint was not instrumented because tests concerning the spinal column were not conducted (see Section 3).

2.1 Design of Exoskeletal Joints

The manner in which the three basic exoskeletal joints have been combined in order to allow movement at each of the wearer's joints is presented in detail in Reference 1, and will not be repeated here. However, movement of the scapula, or shoulder girdle, was found to cause large bearing forces between the exoskeleton and the wearer when the basic joints were combined as discussed in Reference 1. Further, forward flexion and hyperextension of the spinal column caused the upper portion of the exoskeletal spinal column to rotate relative to the wearer's back which, in turn, caused the exoskeleton to exert large forces against the wearer's back, and caused the exoskeletal shoulder joints to pull away from the wearer's shoulders. The above two interferences between the wearer and the exoskeleton required altering the preliminary design in the following manner.
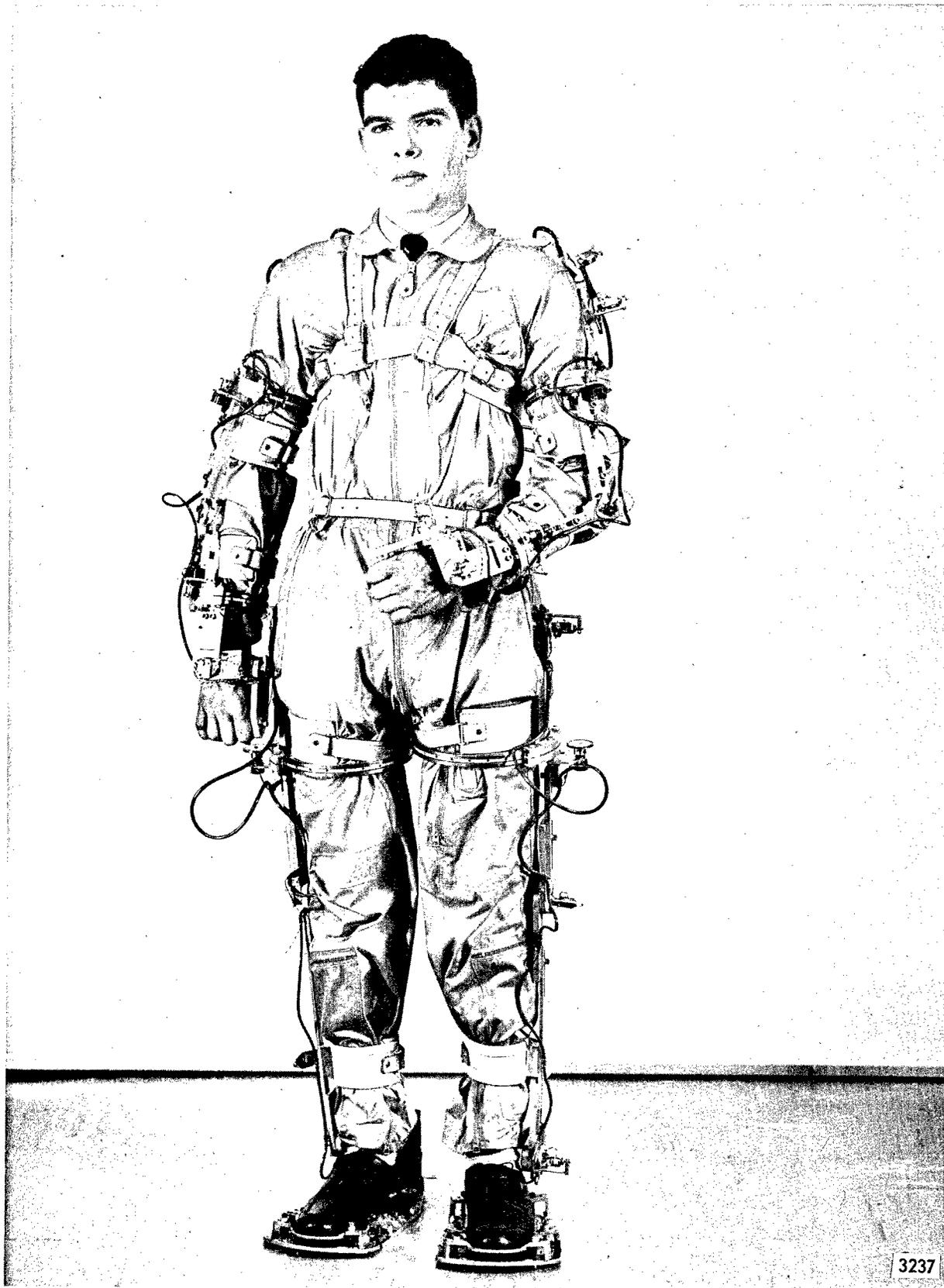
Figure 1   EXOSKELETAL STRUCTURE - FRONTAL VIEW

Figure 3   EXOSKELETAL STRUCTURE - 3/4 FRONT VIEW

2.1.1   Scapula Movement

The scapula can be abducted, adducted and rotated. These motions were permitted in the preliminary design of the exoskeleton by four axes of rotation, two for each shoulder, that were located near the mid-sagittal plane at the back of the wearer. After the exoskeleton was fabricated it was found that the above design of the exoskeletal joints caused the exoskeletal shoulder joint to interfere with the wearer's shoulder and neck, and thus the exoskeleton prevented the wearer from elevating his arms sidewards above a horizontal position. The interference was removed by eliminating the four exoskeletal axes of rotation that were intended to permit scapula movement, and by supporting the exoskeletal shoulder joints by a rigid link attached to the upper portion of the exoskeletal spinal column (see Figure 2). The rigid link was adjustable in length to allow for the different shoulder widths of different subjects.

In the altered design, scapula movement was permitted by axes of rotation located in the exoskeletal shoulder joint. Sideward elevation was permitted because the exoskeletal shoulder joint was not located above the shoulder of the wearer. However, when the wearer's arm is in a horizontal position an exo-skeletal axis of rotation does lie above his shoulder, and thus forward flexion is possible after the arm is elevated sidewards, (Figure 4). The exoskeletal shoulder joint that lies above the wearer's shoulder is partially behind the wearer's back and thus does not prevent sideward elevation of the arm. (A detailed description of the mobility of the above design of the exoskeletal shoulder is contained in Section 3.2 of this report.)

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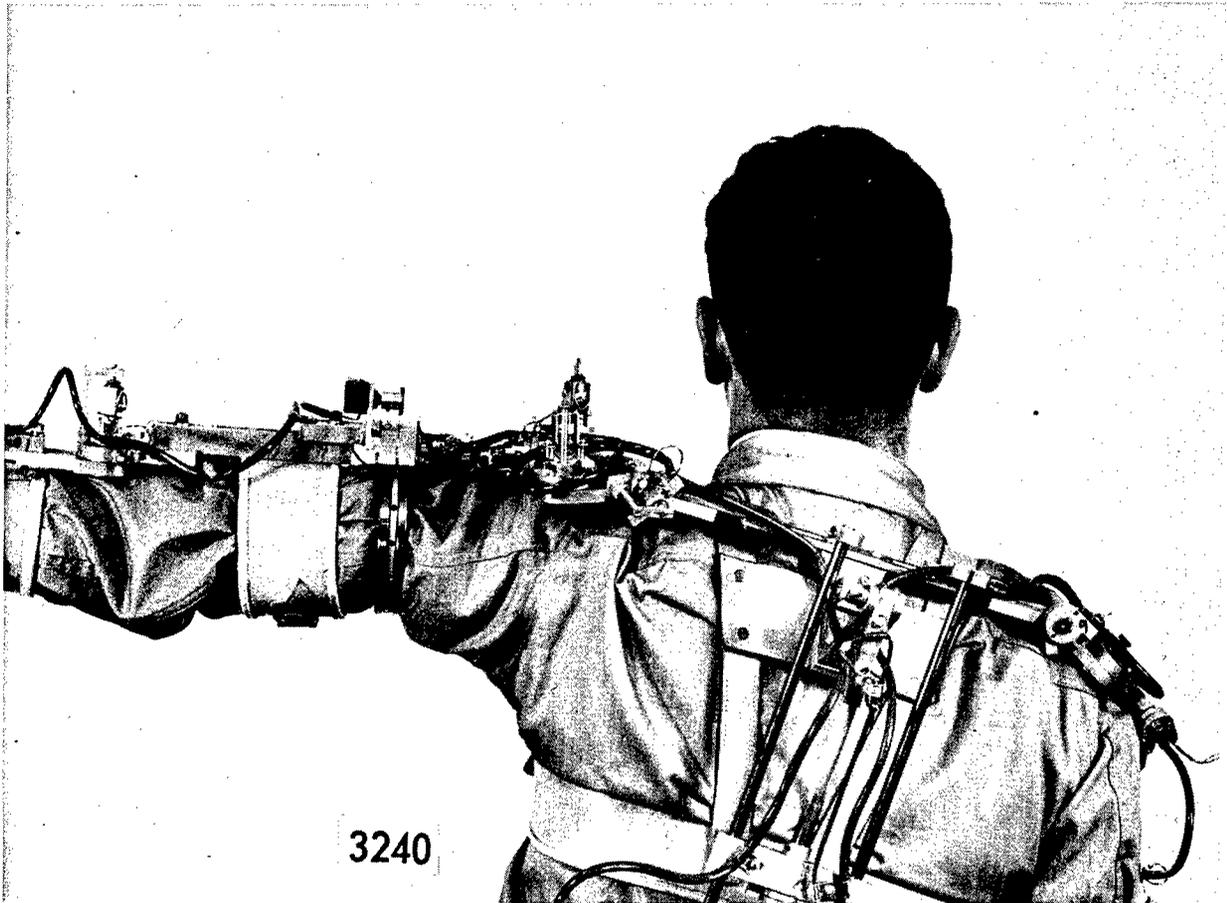
Figure 4 REVISED EXOSKELETAL SHOULDER JOINT

2. 1. 2   Spinal Column Movement

        In the preliminary design of the exoskeleton, flexion and hyperextension of the spinal column were permitted by an axis of rotation perpendicular to the sagittal plane and located near the wearer's waist. After the exoskeleton was fabricated, it was found that the upper portion of the exoskeletal spinal column must contain an axis of rotation parallel to the above axis. The upper axis of rotation is necessary in order to prevent the exoskeletal shoulder joint from being forced backwards, away from the wearer's shoulder, during forward flexion of the spinal column. The added axis of rotation can be seen at the upper portion of the exoskeletal spinal column in Figure 2.

2. 2   Design of Exoskeletal Body Attachments

        The following factors are considered requirements for proper design of the exoskeletal body attachments: (a) the attachments must be adjustable in size in order to fit different individuals, (b) the attachments must be able to transfer required forces and, in certain cases, moments from the wearer to the exoskeleton, in order to cause the exoskeleton to follow movements of the wearer, (c) the attachments must not in themselves restrict movements of the wearer, (d) the attachments must be easily attached to and removed from the wearer, and (e) the attachments must be comfortable.

        Exoskeletal body attachments perform two functions. They must, of course, cause the exoskeletal limbs to follow the wearer's limbs. They must also, however, remove the effect of redundant exoskeletal axes of rotation. For example, if the wearer's arm is straight the exoskeletal axis that permits internal and external rotation of the upper arm is aligned with the exoskeletal axis that permits internal and external rotation of the wrist, and consequently, the exoskeleton is not, by itself, constrained to follow the movements of the wearer. In other words, in the above example, if the wearer's arm is straight and horizontal, and the noted axes are aligned, the body attachments must prevent the portion of the exoskeleton between the two aligned axes from rotating relative to the wearer from the effect of gravity. The body attachments must provide,

therefore, a degree of restraint when the exoskeletal axis is aligned.

In accordance with the above criteria, the exoskeletal body attachments were located at the following positions: midway between the ankle and calf, thigh, waist, chest, midway between the biceps and elbow, and midway between the elbow and wrist. In addition to the above attachments, the wearer's shoes were clamped to the exoskeletal shoe plates, and hand grips were provided at each exoskeletal wrist joint. The straps that attach the exoskeletal arms and legs to the wearer were 2 inches wide, and were made adjustable by use of "Vel-cro" material[*].

The waist and chest body attachments are required to support relatively large segments of the exoskeleton. Thus, the above attachments were fabricated with sheets of aluminum sandwiched between sheets of leather. In that way bearing forces act over a large area of the wearer's body and discomfort is reduced.

2.3   Instruments Installed on the Exoskeleton

In order to measure the range of motion, velocity and acceleration that occur at each exoskeletal joint, and the frequency of use of the available range of motion, position sensors were designed, fabricated and installed on the exoskeleton. The sensors were used to measure the angular position of each joint as a function of time. The output of each sensor was recorded. The velocity and acceleration of each joint was computed by graphically differentiating the time history of position. Frequency of use of the allowable or available range was computed by determining the percentage of time that the position of a given joint exceeded or equaled a given value.

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[*]   Vel-cro is a form of nylon manufactured such that two mating surfaces cling together when they are pressed together. The material was used, in the above application, to perform the function that buckles usually perform in securing straps to a person's body.

2.4   Physical Properties of the Exoskeleton

The weight, inertia and static moment of limb segments of the exoskeleton are presented in Table 1. Corresponding values for an adult male weighing 180 lbs are shown in Table 1 to provide a means for comparison. The following is a description of the methods used to compute values for the exoskeleton that are shown in Table 1.

The weight of limb segments of the exoskeleton was measured directly, and the center of gravity of the limb segments was located by balancing each limb segment on a knife edge. The values of static moment shown were computed by multiplying the static weight of a limb by the distance from the center of gravity of the limb to the joint center. For example, the static moment shown for the arm (7. 65 ft-lbs) is equal to the weight of the limb (8. 65 lbs) multiplied by the distance from the center of the shoulder to the center of gravity of the upper arm, the forearm and the wrist, combined (0. 885 ft).

The moment of inertia of exoskeletal limb segments was determined by recording the natural period of oscillation for each segment. The equation of motion for a pendulum is

$$I \frac{d^2\theta}{dt^2} + W d \sin \theta = 0$$

where   I   =   moment of inertia of the pendulum about the axis of rotation - lb-ft-sec^2,

θ   =   angle between the center line of the pendulum and the vertical - rad,

W   =   weight of the pendulum - lbs,

d   =   distance between the axis of rotation and the center of gravity - ft

t   =   time, sec.

LIMB SEGMENT	JOINT USED TO DETERMINE INERTIA AND STATIC MOMENT	WEIGHT lbs			INERTIA lbs-ft-sec^2			STATIC MOMENT ft-lbs		
		Human (2)	Exoskeleton (1)	% (3)	Human	Exoskeleton	% (3)	Human	Exoskeleton	% (3)
Arm	Shoulder	8.65	6.6	76.3	0.397	0.16	40.3	7.65	4.16	54.5
Forearm	Elbow	3.78	3.0	79.4	0.16	0.03	18.7	1.56	3.67	235
Leg	Hip	28.3	9.7	34.2	3.92	1.21	30.9	40.9	1.5	3.7
Lower Leg	Knee	10.8	4.75	44.0	1.55	0.263	17.0	7.25	5.54	76.4
Foot	Ankle	2.5	4.0	160.0	0.079	0.212	268.0	0.625	1.33	213

NOTES:

(1) The total weight of the exoskeleton is 34.6 lbs.

(2) Weights shown correspond to an adult male weighing 180 lbs. Values shown were computed by use of Reference 3.

(3) Percentages shown are the increases in each measure due to wearing the exoskeleton.

TABLE 1 - PHYSICAL PROPERTIES OF THE EXOSKELETON

For small amplitudes, sin θ may be assumed to be equal to θ, and the equation of motion reduces to

$$\frac{d^2\theta}{dt^2} + \frac{W d}{I}\,\theta = 0.$$ (1)

One form of the general solution of Equation (1) is

$$\theta = A \sin \omega t + B \cos \omega t,$$ (2)

where   A and B = arbitrary constants

          ω = angular frequency of oscillation - rad/sec,

$$= \sqrt{\frac{W d}{I}}$$

When the angle $\omega t = 2\pi$ rad a cycle of motion is completed and thus the natural period of oscillation is

$$T = \frac{1}{2\pi} \sqrt{\frac{W d}{I}} \quad \frac{cyc}{sec}$$

Thus, if T, W and d are known, the moment of inertia of the limb segment relative to the axis of rotation can be computed:

$$I = \frac{W d}{4\pi^2 T^2} \quad \text{lb-ft-sec}^2.$$

3. TESTS CONDUCTED WITH THE EXOSKELETON

The purpose of the tests that were conducted was (1) to determine, by experiment, the minimum number of joints necessary to enable the wearer to perform useful work tasks, and (2) to determine the mean and maximum velocities at each joint for use in estimating power requirements for future powered versions of the Man Amplifier. The tests conducted can be divided into tests concerned with the lower extremity (the hips, legs and feet) and tests concerned with the upper extremity (the shoulders, arms and wrists). Tests concerned with the spinal column were not conducted because it was found that, (1) eliminating any particular motion at the exoskeletal spinal column prevented the subject from performing normal work tasks (bending, sitting, picking up loads, etc.) and (2), that the range of motion at any particular exoskeletal joint in the spinal column was so small that restricting the motion partially was not practical. Tasks chosen for the lower extremity tests were: walking, running, stair climbing, and load carrying. Tests chosen for the upper extremity were: general measures of shoulder mobility and general ability to perform typical control tasks.

3.1 Tests Concerning the Lower Extremity

Tests of walking were performed without the exoskeleton, with the exoskeleton without motion restrictions at the exoskeletal joints, and with the exoskeleton but with the allowable range of movement at certain joints limited. Tests of running, stair climbing and load carrying were performed only with the exoskeleton, with motion unrestricted at the exoskeletal joints.

During all of the tests conducted, it was found that the exoskeletal joint to permit abduction and adduction of the ankle was unnecessary. Consequently, during all tests the above exoskeletal joint was locked-out. (The exoskeletal joint that was locked-out is noted in Figure 17.)

Tests to determine the effect of limiting the allowable range of joint movement on walking were conducted in the following manner. The subject walked a prescribed distance (20 feet), first, without the exoskeleton, second, with the exoskeleton but without motion restrictions at the exoskeletal joints, and third, with the allowable range of motion at certain exoskeletal joints limited. The subject attempted to expend energy at a constant rate regardless of the particular test being conducted. In other words, the subject reduced his speed of walking when various joint motions were limited in order to make the rate of expended energy constant. Consequently, the time required to walk the prescribed distance was related to the effect of limiting the allowable range of joint motion.

The ability of the subject to judge his rate of expending energy was tested by measuring the performance of the subject at different times for the same restriction. It was found that while there was a significant difference between means at the 90% confidence level, the difference was approximately 10%. The level of accuracy of the tests required in order to draw the desired conclusions is far less than 90%, therefore, it was concluded that the subject could control his rate of expending energy with sufficient accuracy for the purpose at hand.

Each test configuration was performed a total of eight times. The time required to walk the prescribed distance was recorded for each run, and the data were analyzed as follows.

The mean value and standard deviation of the walking time was computed for each test configuration by use of statistical techniques. The hypothesis that the mean values for different configurations were equal was tested by use of the "t" distribution (Reference 4, page 124). The 95 percent confidence interval for the difference between means was computed by use of the method presented in Reference 4, page 128.

It was found that limiting the allowable range of joint motion in any manner tested resulted in a significant decrease of performance. In other words, the hypothesis that the mean values for any two test configurations are equal was rejected at the 95 percent level of significance.

Table 2 presents the 95 percent confidence limits for the performance decrement in walking caused by limiting the allowable range of movement at the hip, knee, ankle, and foot. (For example, the probability that walking performance is degraded between 26.2% and 40.8% when knee flexion is limited to a range of 9° is 0.95.) The performance decrement presented is defined as the percent decrease in walking velocity that is caused by the particular restriction. Tests were conducted with one joint restricted for each test configuration, and consequently it is not possible to use the data presented in Table 2 to draw conclusions concerning the effect of limiting motion at more than one joint. The median of the confidence limits shown in Table 1 is presented graphically in Figure 5.

A brief analysis of the effect of limiting the allowable range of motion at more than one joint was conducted.[*] The subject walked a distance of 15 feet, and the time required to walk the distance was recorded for a measure of performance. The data were analyzed statistically, and the following conclusions were drawn (at the 95 percent level of confidence).

1.   Limiting hip flexion to 27 degrees and knee flexion to 18 degrees does hinder walking.

2.   Limiting hip flexion to 27 degrees and knee flexion to 36 degrees does hinder walking.

3.   Limiting hip flexion to 36 degrees and knee flexion to 18 degrees does hinder walking.

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[*]   Tests were conducted by Messrs. Charles Clauser and Lloyd Laubach of the Anthropology Branch, Human Engineering Division, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base.

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Figure 5

PERFORMANCE DECREMENT FOR WALKING LIMITATIONS
VS
LIMITATIONS IN ALLOWABLE LEG MOVEMENT

	Complete Freedom	HIP 27°	HIP 18°	HIP 9°	HIP 0°	KNEE 27°	KNEE 18°	KNEE 9°	KNEE 0°	ANKLE 18°	ANKLE 9°	ANKLE 0°	FOOT 0°
HIP 27°	4.30	18.4	32.7	48.9	69.0								
18°	23.0	10.0	16.8	32.9	20.4								
9°	33.9	19.5	7.45	25.8	36.0								
0°	60.4	19.6	31.0	38.8	59.0								
KNEE 27°	12.15					19.6	27.8	40.8	59.5				
18°	17.7					2.45	11.2	27.0	10.6				
9°	26.2					11.3	4.4	23.0	18.8				
0°	55.5					3.53	6.28	44.0	53.7				
ANKLE 18°	4.31									6.66	20.0	57.6	
9°	18.05									7.8	19.9	19.2	
0°	50.2									9.82	49.0	56.9	
FOOT 0°	16.1												22.4

(Diagonal division labeled UPPER LIMIT above and LOWER LIMIT below.)

TABLE 2 - PERFORMANCE DECREMENT IN WALKING CAUSED BY RESTRICTING ALLOWABLE LEG MOVEMENT

4. Limiting hip flexion to 36 degrees and knee flexion to 27 degrees does hinder walking.

5. Limiting hip flexion to 36 degrees and knee flexion to 36 degrees does not hinder walking.

The time history of joint positions during walking (while wearing the exoskeleton) are presented in Figures 6, 7 and 8. The above noted figures represent motion parallel to the sagittal plane at the hip, knee and ankle, or in other words, flexion and extension of the hip, knee and ankle. Figure 6 presents motion during one pace for straight walking at normal, or average, speed. Figure 7 presents the above data wherein the subject is running at a fairly slow pace. Figure 8 presents the above data for the case where the subject is running nearly as rapidly as possible.

Figure 9 presents joint velocity of the lower extremity during straight walking at a normal speed. The curves shown represent the percentage of time that the velocity of the particular joint is equal to or greater than the given value. For example, from Figure 9, the velocity of the knee joint equals or exceeds 255 degrees per second 20 percent of the time during straight, level walking. Figure 10 presents acceleration of leg joints during normal walking in the manner discussed above. Data representing the velocity and acceleration of lower extremity joints during rapid running are presented similarly in Figures 11 and 12.

Figure 13 presents the time history of joint position for the hip, knee and ankle during stair climbing. One pace only is presented. The stairs used have a riser height of six inches and a tread depth of twelve inches. The subject was not able to estimate the energy expended when the data for stair climbing was recorded. Therefore, the rate of stair climbing, in steps per minute, was made equal to the rate of normal walking, in steps per minute. The velocity and acceleration of the lower extremity joints were not computed for stair climbing.
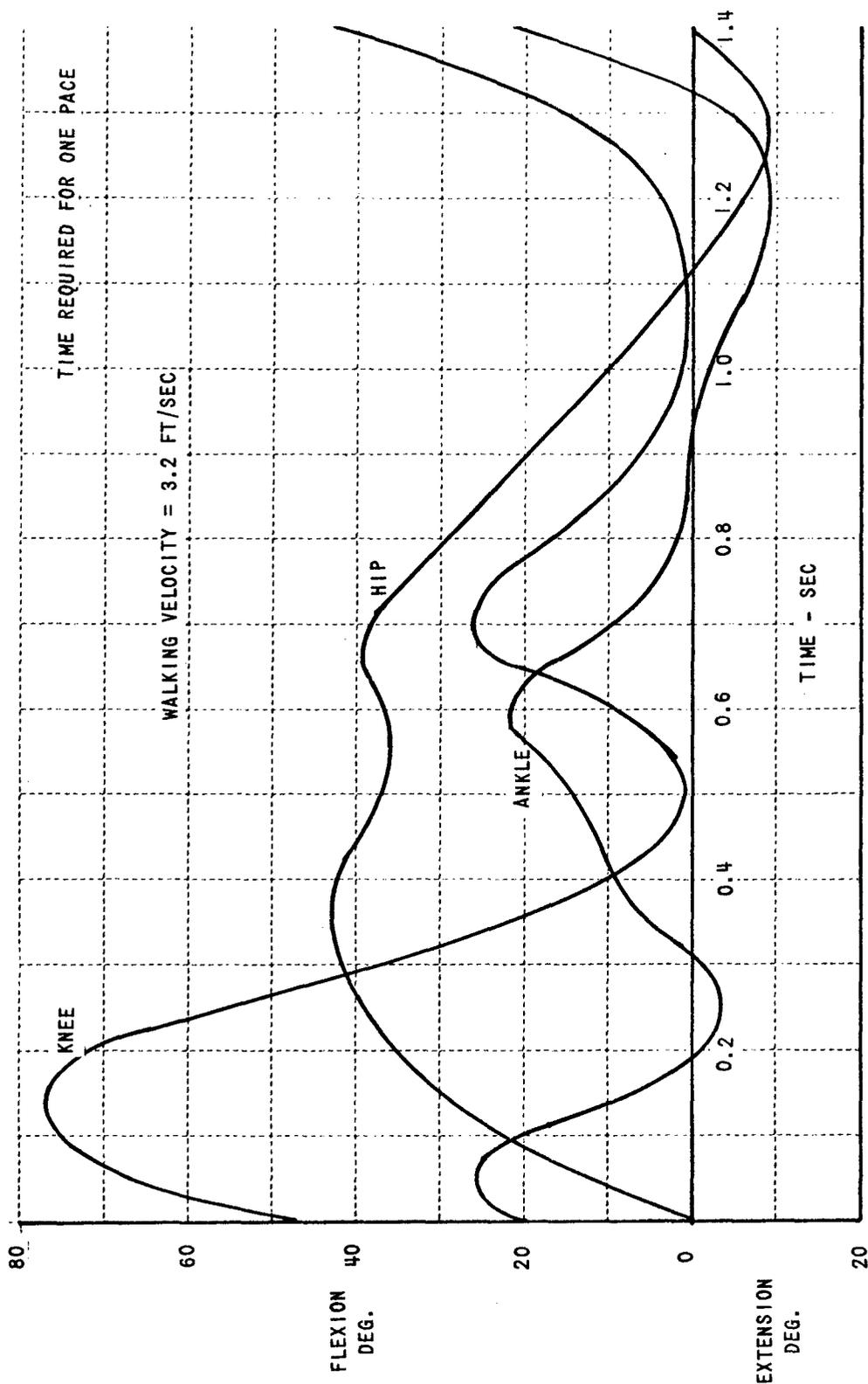
Figure 6

TIME HISTORY OF HIP, KNEE AND ANKLE POSITION DURING STRAIGHT, LEVEL WALKING
NORMAL WALKING RATE
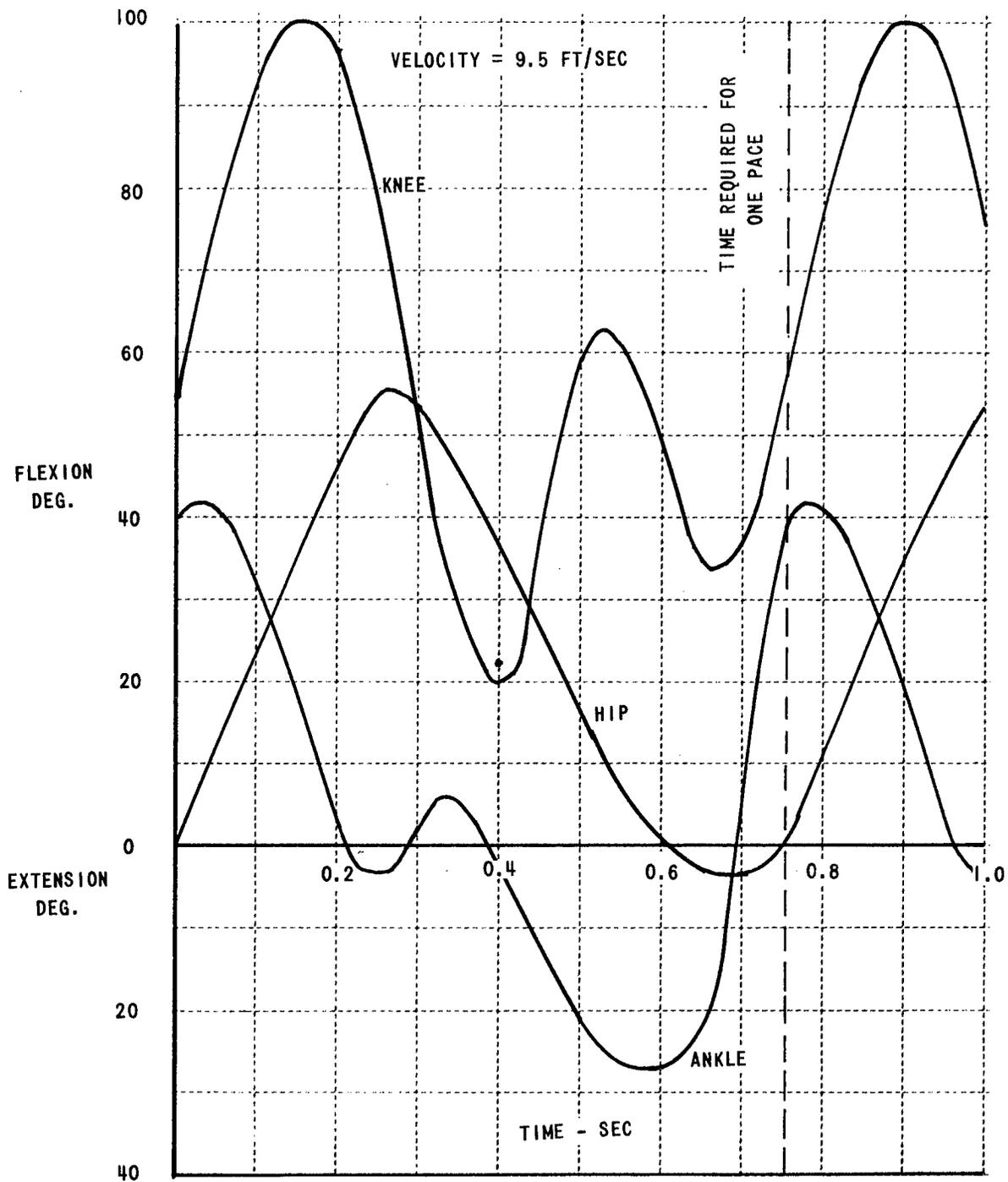
Figure 7

TIME HISTORY OF HIP, KNEE AND ANKLE POSITION DURING STRAIGHT, LEVEL WALKING - SLOW RUN RATE
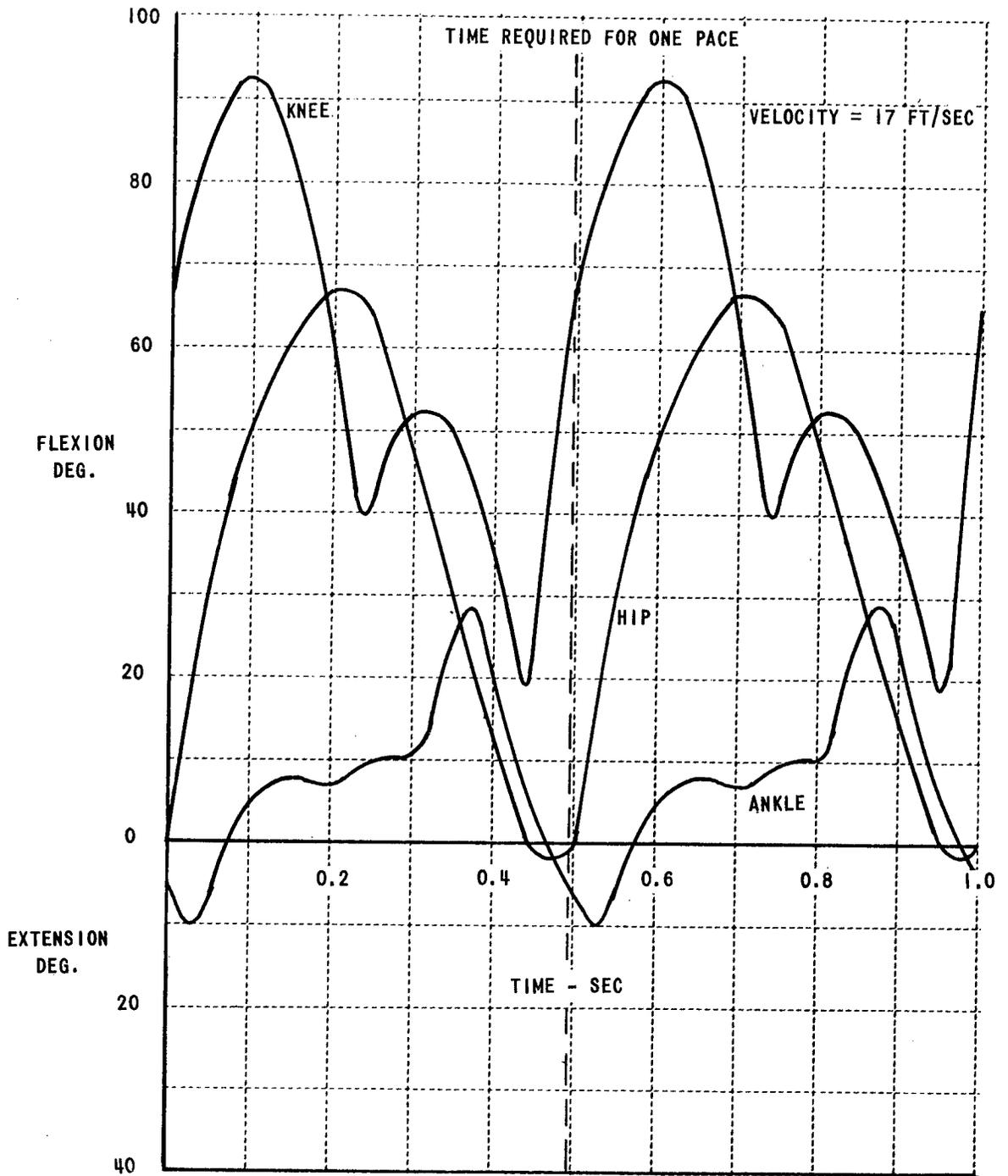
Figure 8

TIME HISTORY OF HIP, KNEE AND ANKLE POSITION DURING STRAIGHT, LEVEL WALKING - RAPID RUN RATE
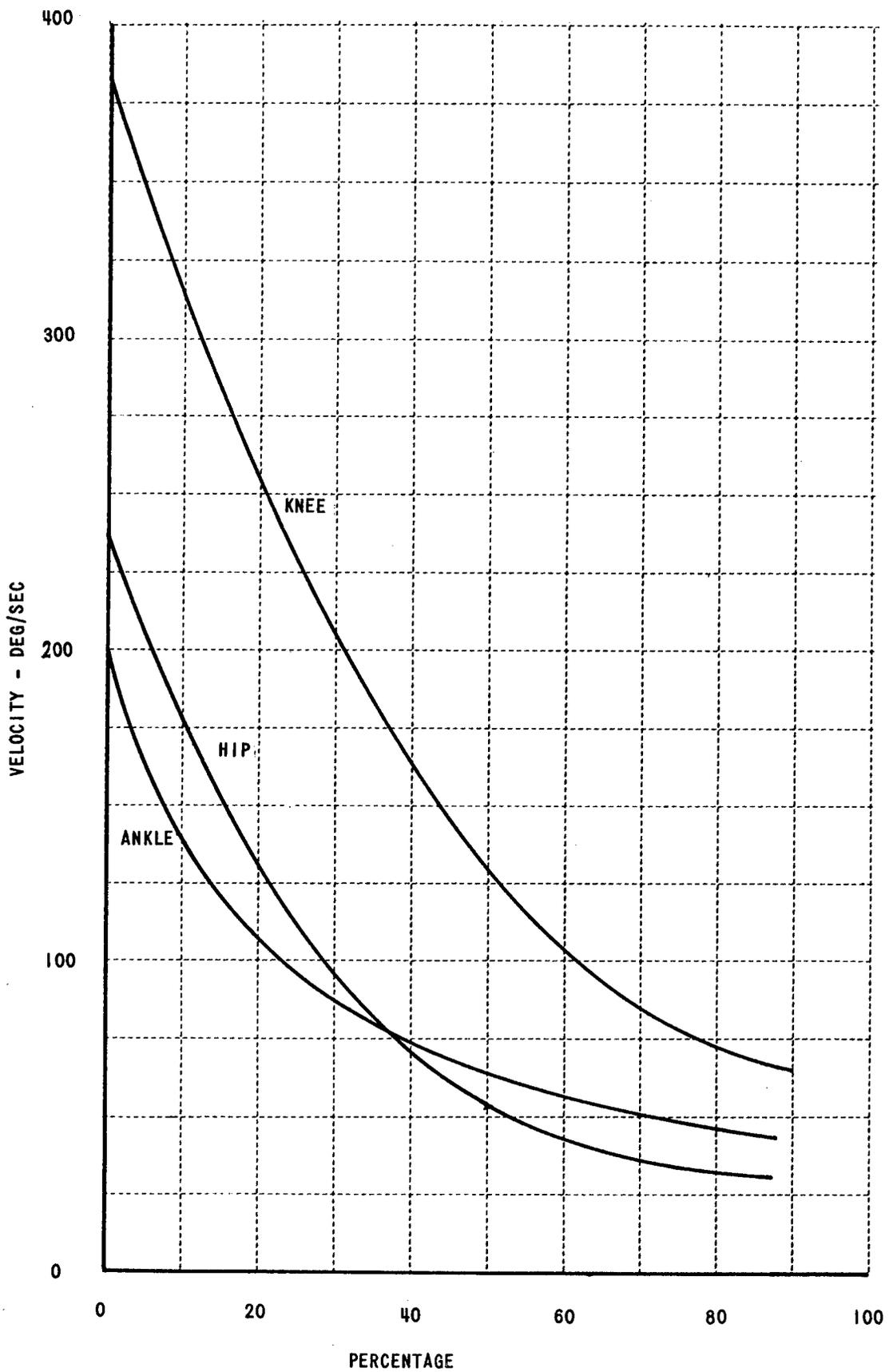
Figure 9

VELOCITY OF HIP, KNEE AND ANKLE DURING STRAIGHT, LEVEL WALKING – NORMAL WALKING RATE
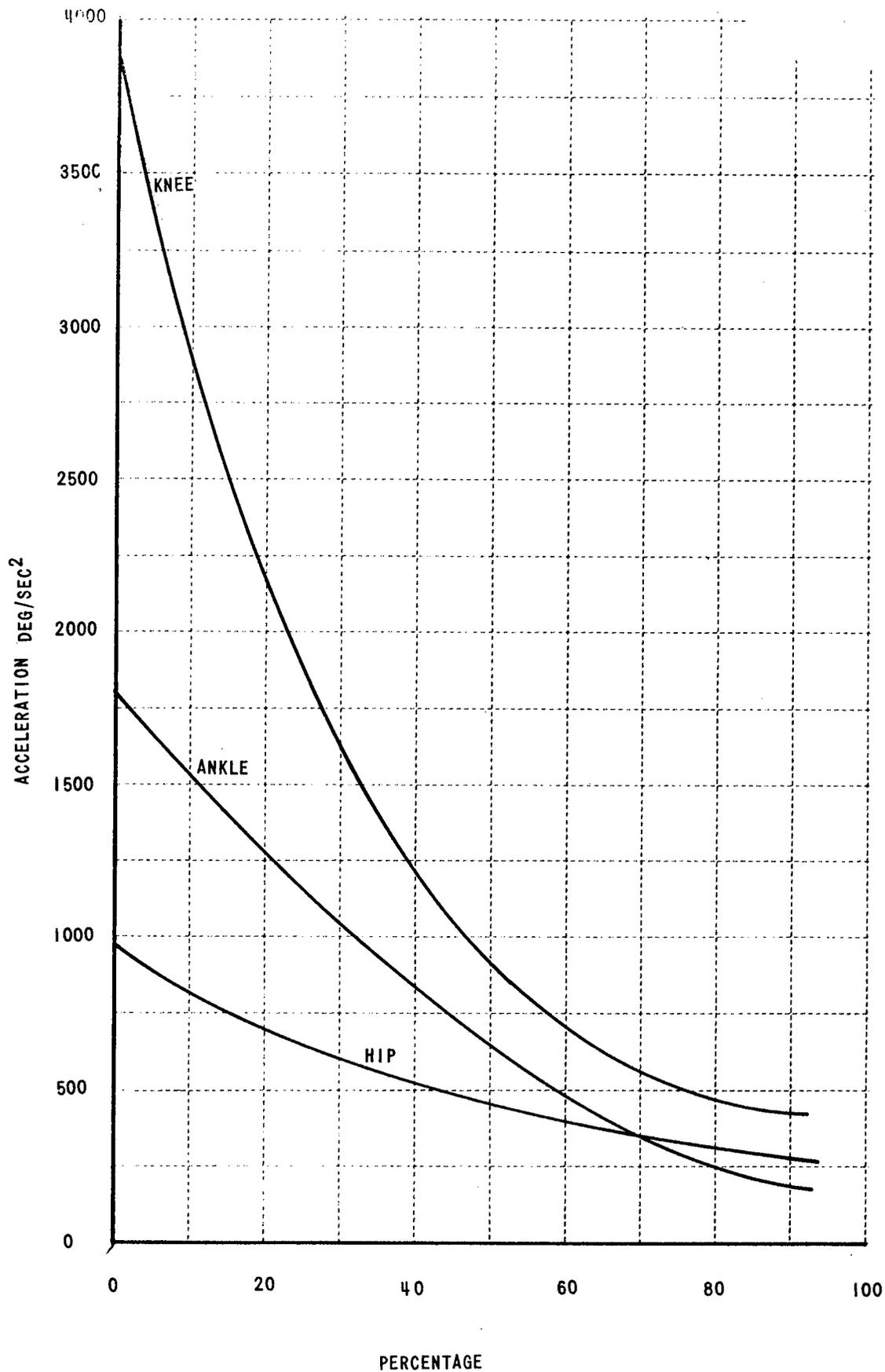
Figure 10

ACCELERATION OF HIP, KNEE AND ANKLE DURING STRAIGHT, LEVEL WALKING – NORMAL WALKING RATE
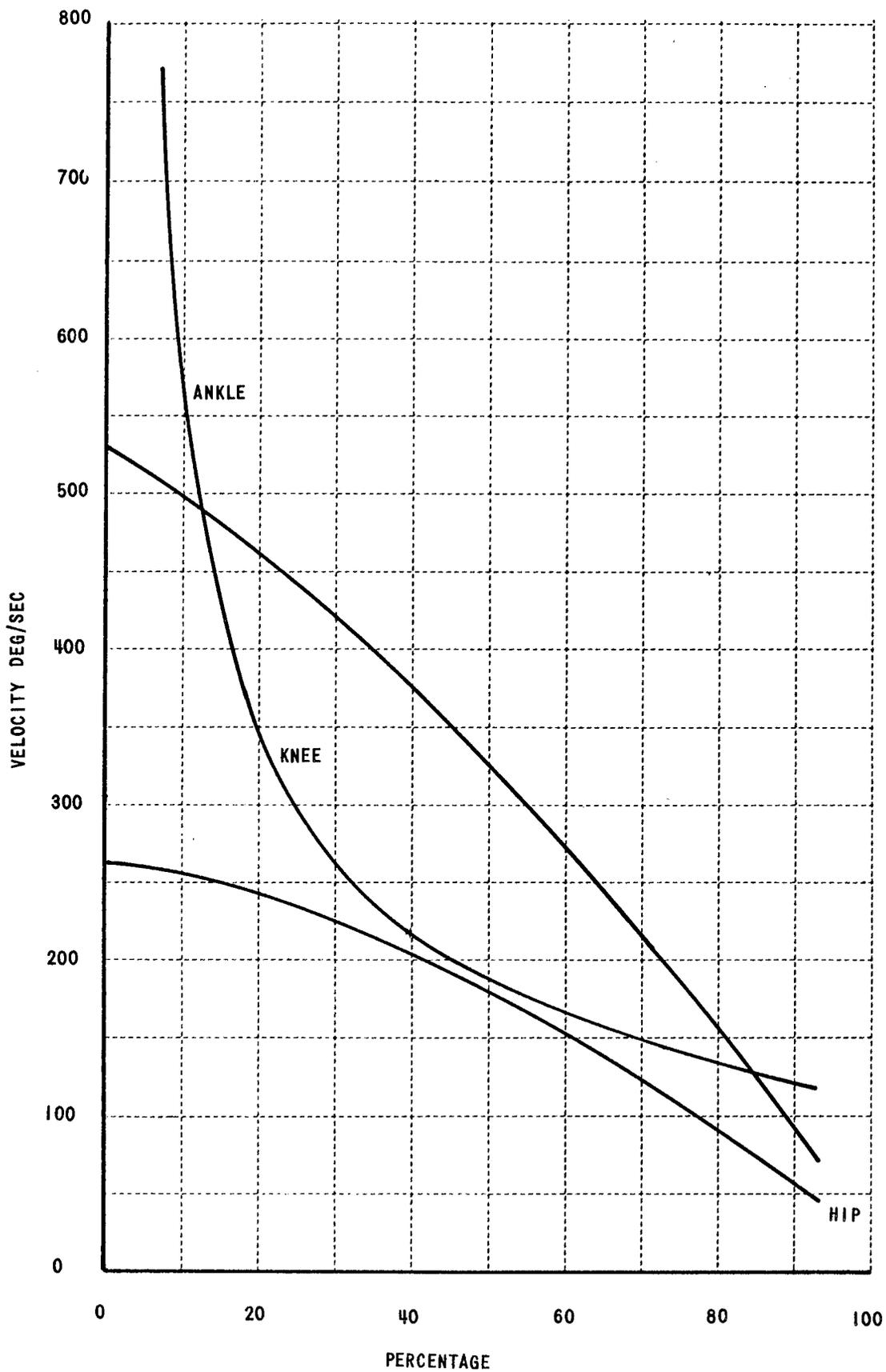
Figure II

VELOCITY OF HIP, KNEE AND ANKLE DURING STRAIGHT LEVEL WALKING – RAPID RUN RATE

VO-1692-V-3
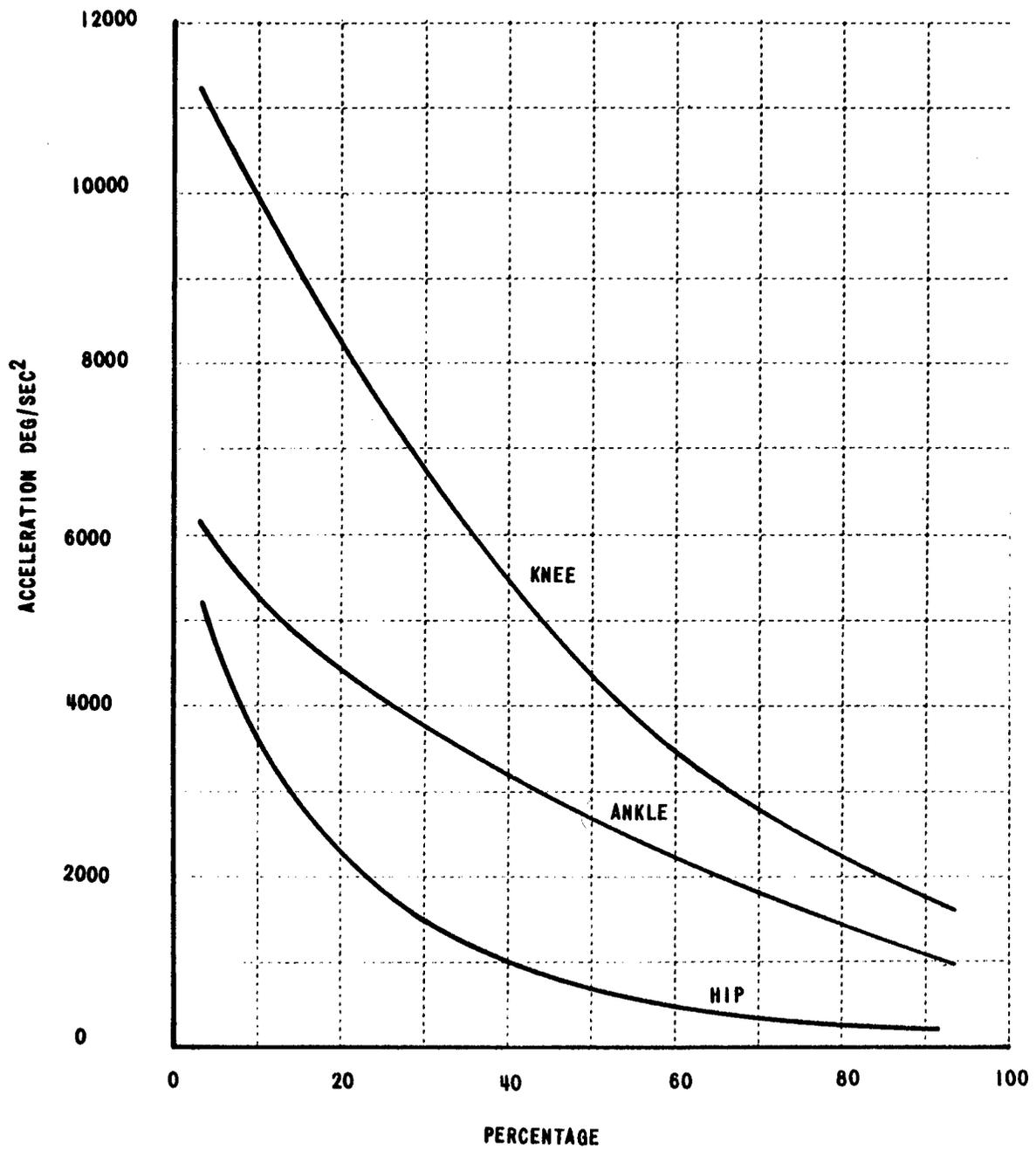
Figure 12

ACCELERATION OF HIP, KNEE AND ANKLE DURING STRAIGHT, LEVEL WALKING - RAPID RUN RATE
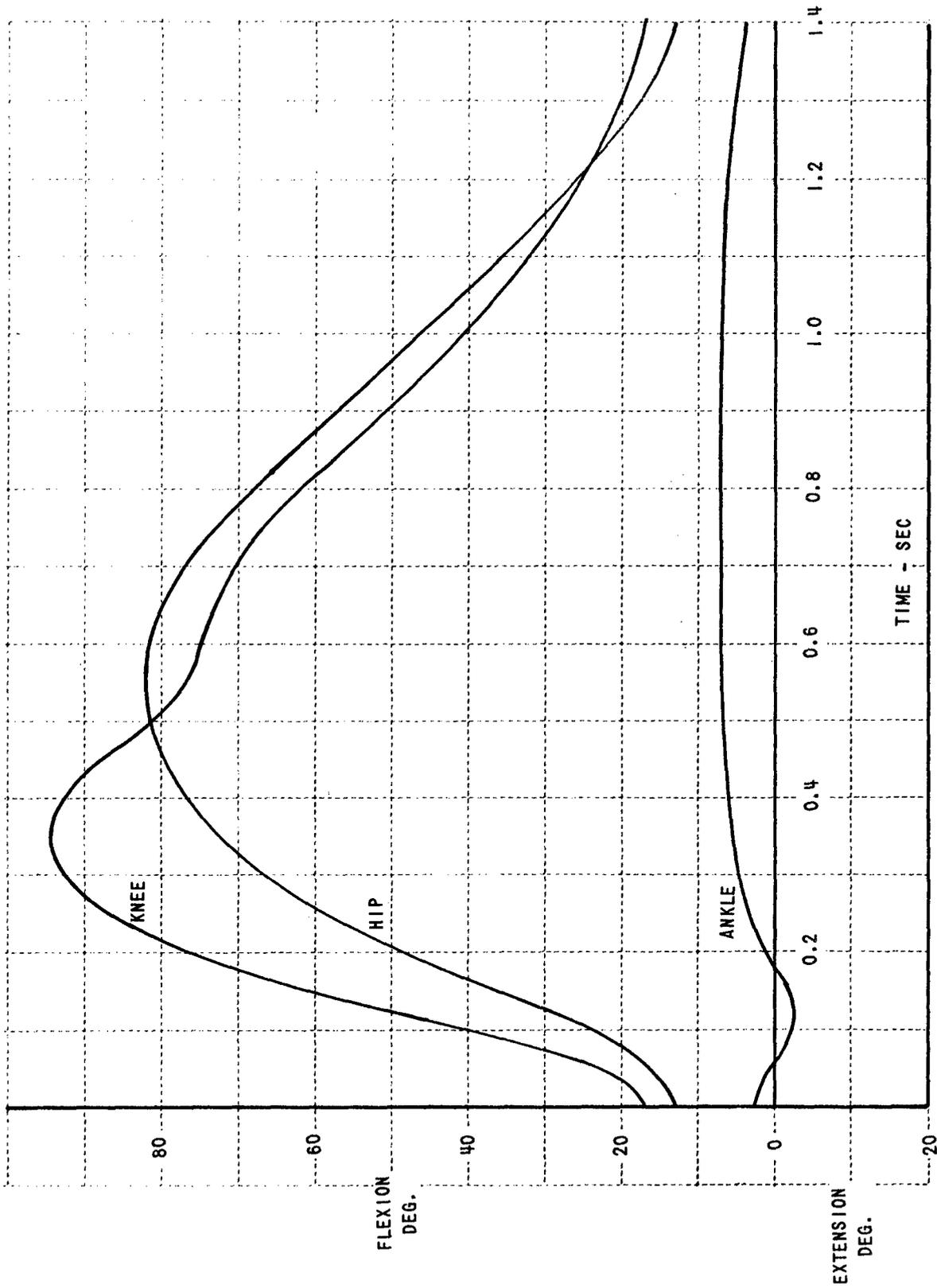
Figure 13

TIME HISTORY OF HIP, KNEE AND ANKLE POSITION DURING STAIR CLIMBING

Motion of exoskeletal joints at the lower extremity were recorded during a load carrying task. The load used was a light-weight wooden box, measuring 2 feet on each side. The task chosen may be broken down into the following subtasks:

1) Pick up load from floor,

2) Back up approximately 3 feet,

3) Turn 90 degrees to the left,

4) Walk forward 5 feet,

5) Turn 90 degrees to the left,

6) Walk sidewards 5 feet,

7) Turn 90 degrees to the right,

8) Walk forward 5 feet,

9) Stop,

10) Rotate torso 90 degrees to the right,

11) Locate load on table, and

12) Release load.

Recordings of joint position with time were obtained throughout the performance of the above described task, and the recordings were analyzed in the following manner.

The time history of joint displacement for each exoskeletal joint on the right leg was tabulated so that the position of the exoskeletal joints was known every 0.1 seconds. Velocity and acceleration were computed by dividing changes in displacement and velocity by the time increment. Values of displacement, velocity and acceleration thus computed are shown in Figures 14, 15 and 16 as a function of percentage of time that the parameter equaled or exceeded the value of the curve. Exoskeletal joint number in Figures 14, 15, and 16 refer to Figure 17. The time period used in the above figures is the total time used to perform the complete load carrying task.
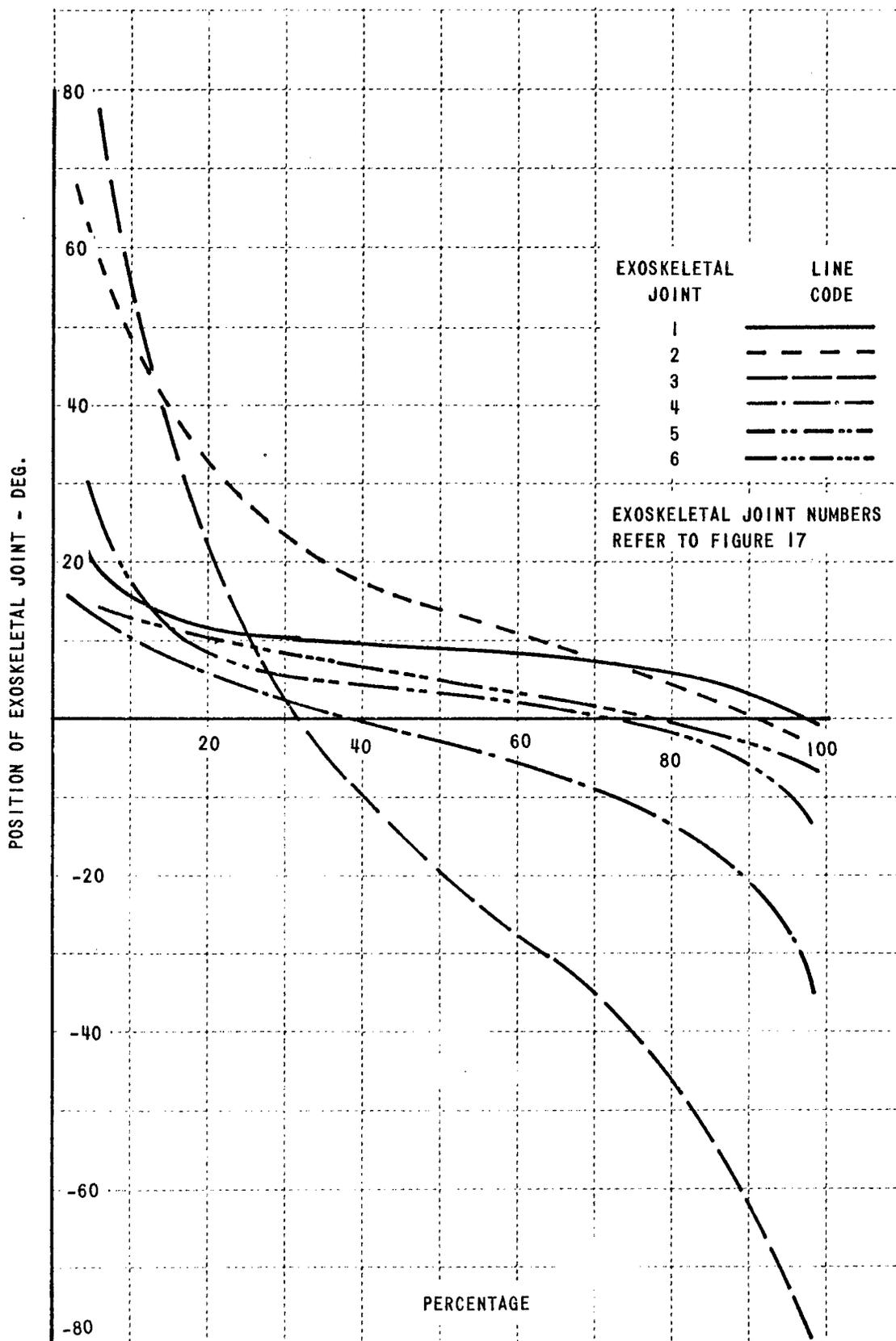
Figure 14   POSITION OF LOWER EXTREMITY EXOSKELETAL JOINTS DURING
LOAD CARRYING
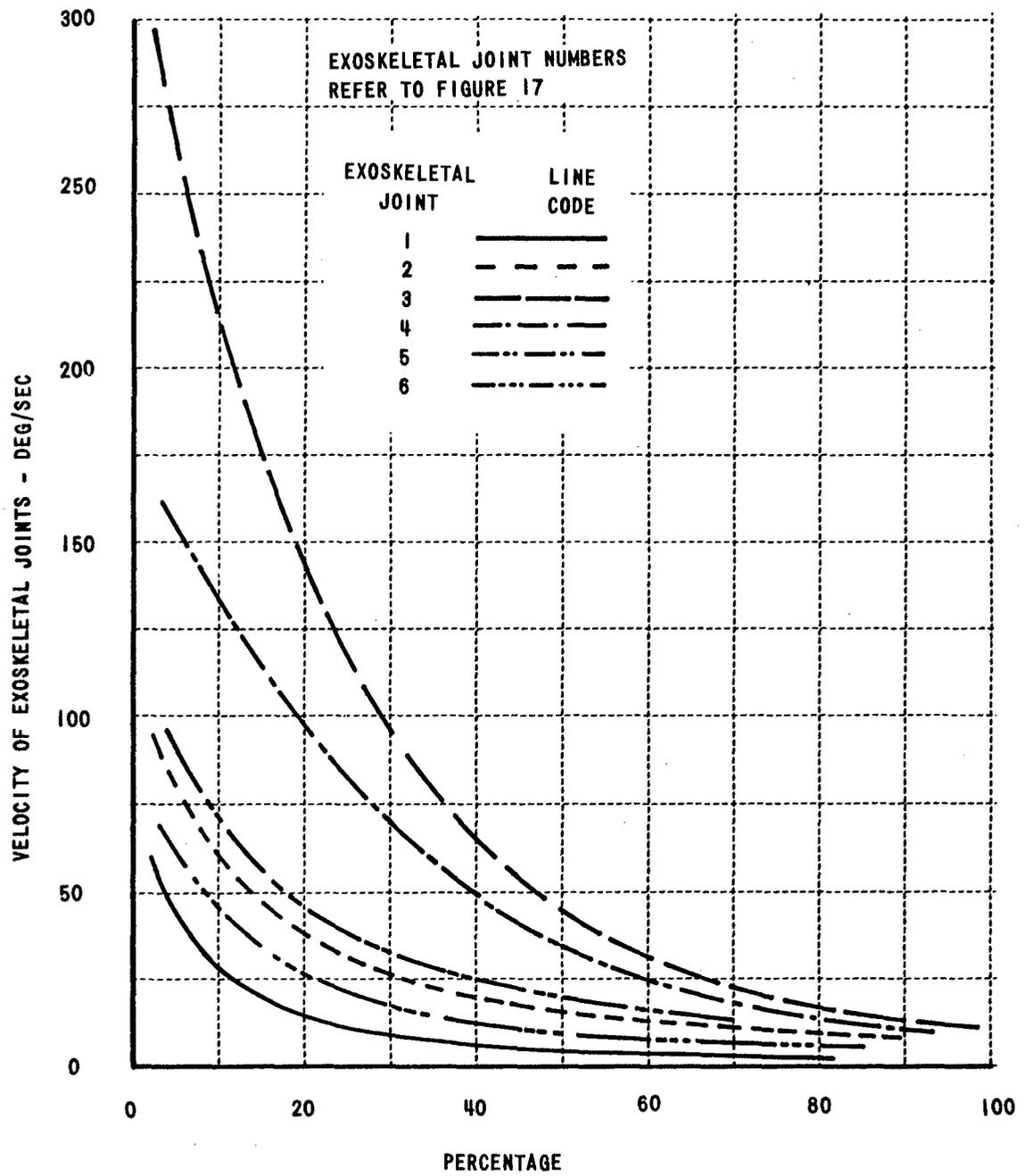
Figure 15
VELOCITY OF LOWER EXTREMITY EXOSKELETAL JOINTS DURING LOAD CARRYING
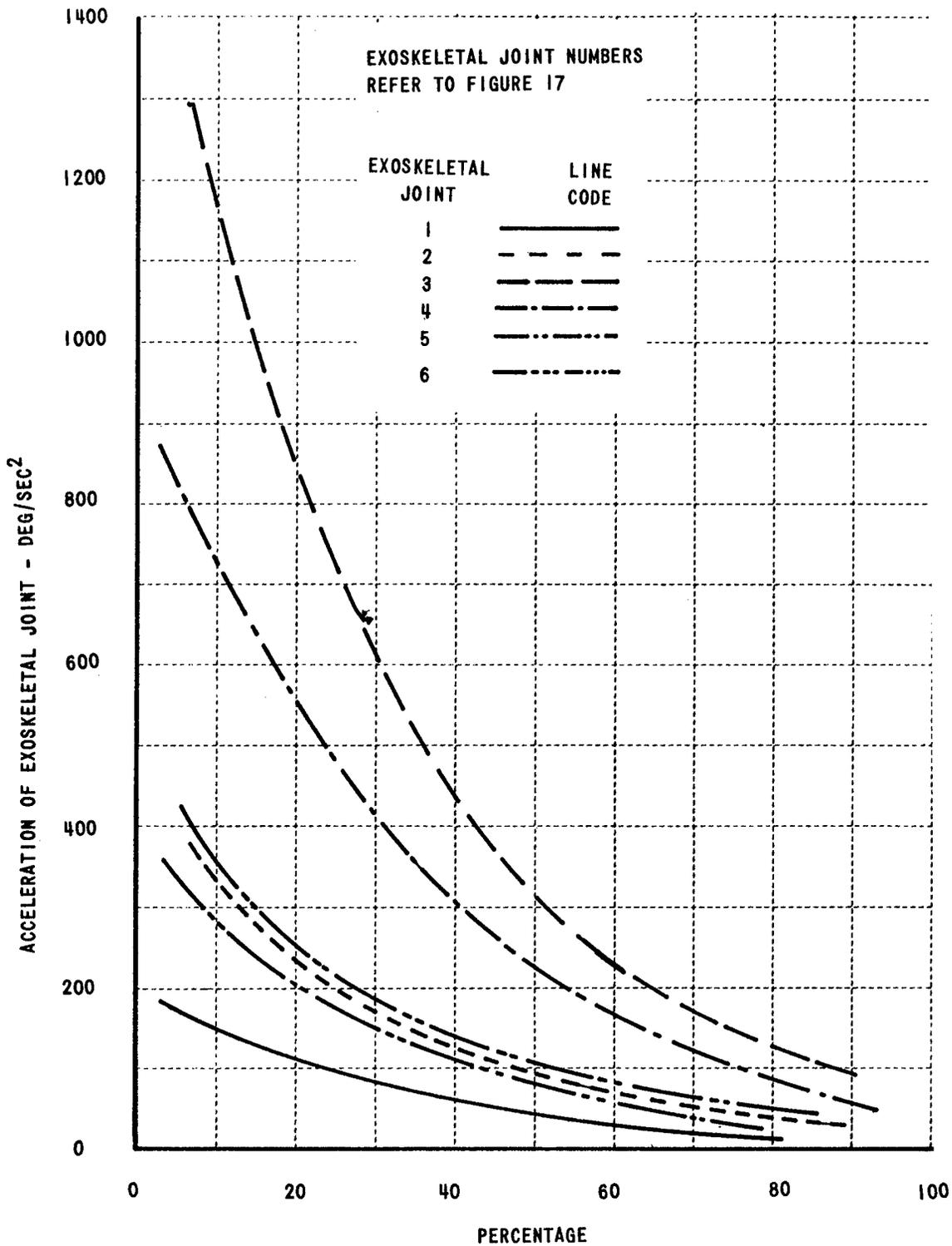
Figure 16
ACCELERATION OF EXOSKELETAL JOINTS DURING LOAD CARRYING

NOTE: THIS JOINT
LOCKED DURING ALL
TESTS

3241
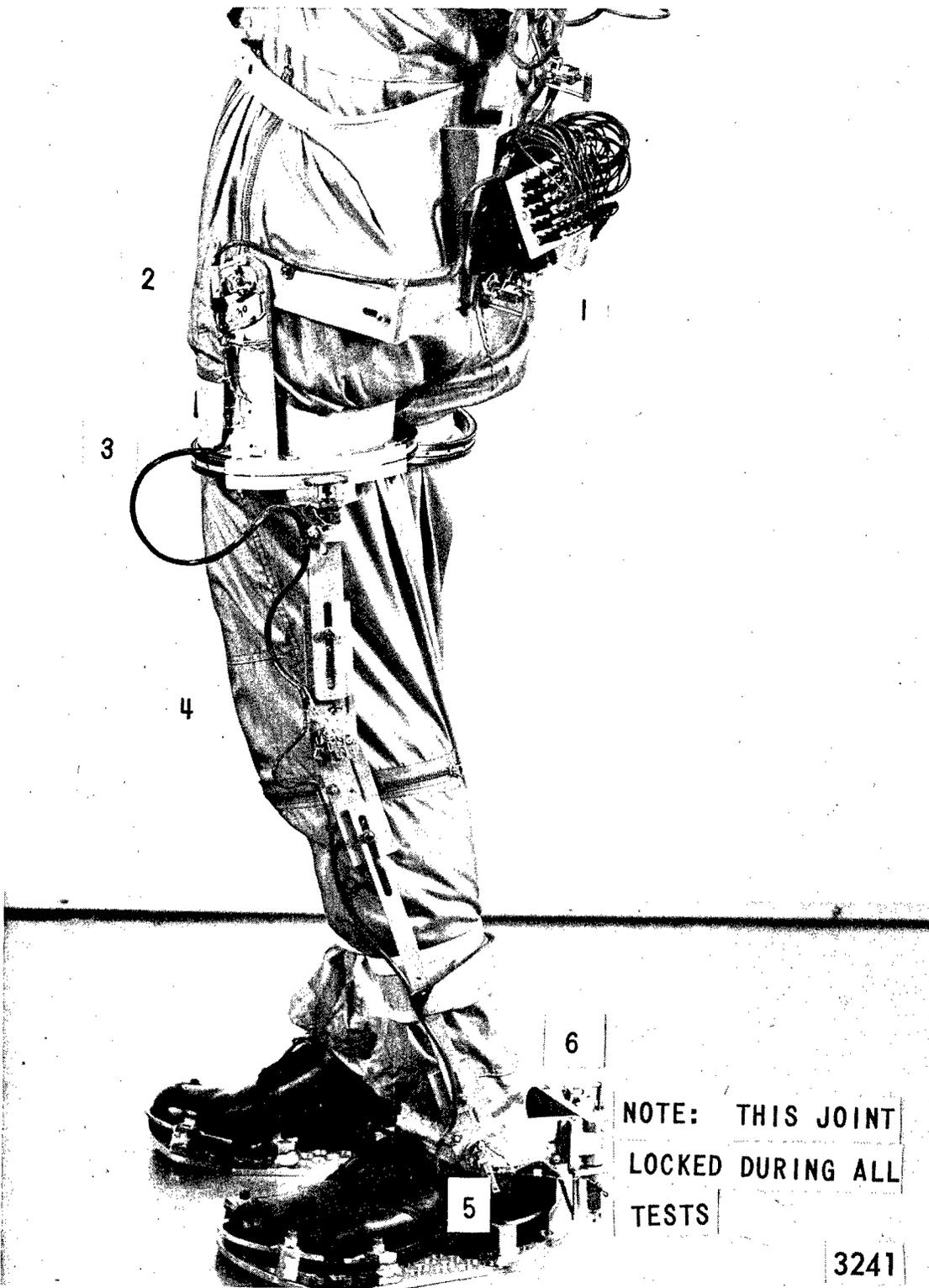
Figure 17   EXOSKELETAL JOINT NUMBERS - LOWER EXTREMITY

3.2   Tests Concerned with the Upper Extremity

As noted earlier, shoulder movement was analyzed in three ways. A shoulder-reach apparatus, shown in Figure 18, was used to determine restrictions in shoulder movements caused by the exoskeleton. A work space apparatus, shown in Figure 19, was used to determine the effect of the exoskeleton on precise shoulder and arm movements. Finally, recordings of positions of exoskeletal joints as a function of time were analyzed to determine values of range, velocity and acceleration that will be encountered with a powered exoskeletal structure. The following is a discussion of each of the above three analyses.

3.2.1   Shoulder-Reach Apparatus*

For operation of the shoulder-reach apparatus the subject is positioned so that the centerlines of the measuring rods pass through the approximate center of his shoulder joint (see Figure 18). The plane containing the measuring rods is positioned relative to the subject by rotating the chair upon which the subject is seated. Thus, data is recorded that represents the reach envelope for all positions of the shoulder. The reach envelope is presented in Figures 20 through 25 by means of horizontal contour lines, each line being located a given distance above the seat reference point. (The seat reference point is located at the intersection of the sagittal plane of the subject, the back of the seat, and the base of the seat.) Each curve represents the reach capability of the subject's right shoulder and arm. The origin of the coordinates lie on a vertical line that passes through the center of the subject's right shoulder joint. The solid lines in Figures 20 through 25 represent shoulder reach without the exoskeleton, and the dashed lines represent shoulder reach with the exoskeleton.

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*   The shoulder-reach apparatus was made available through the courtesy of Messrs. C. Clauser and K. Kennedy of the Anthropology Branch, Human Engineering Division, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base. The data were recorded and reduced under the direction of Mr. Kennedy.
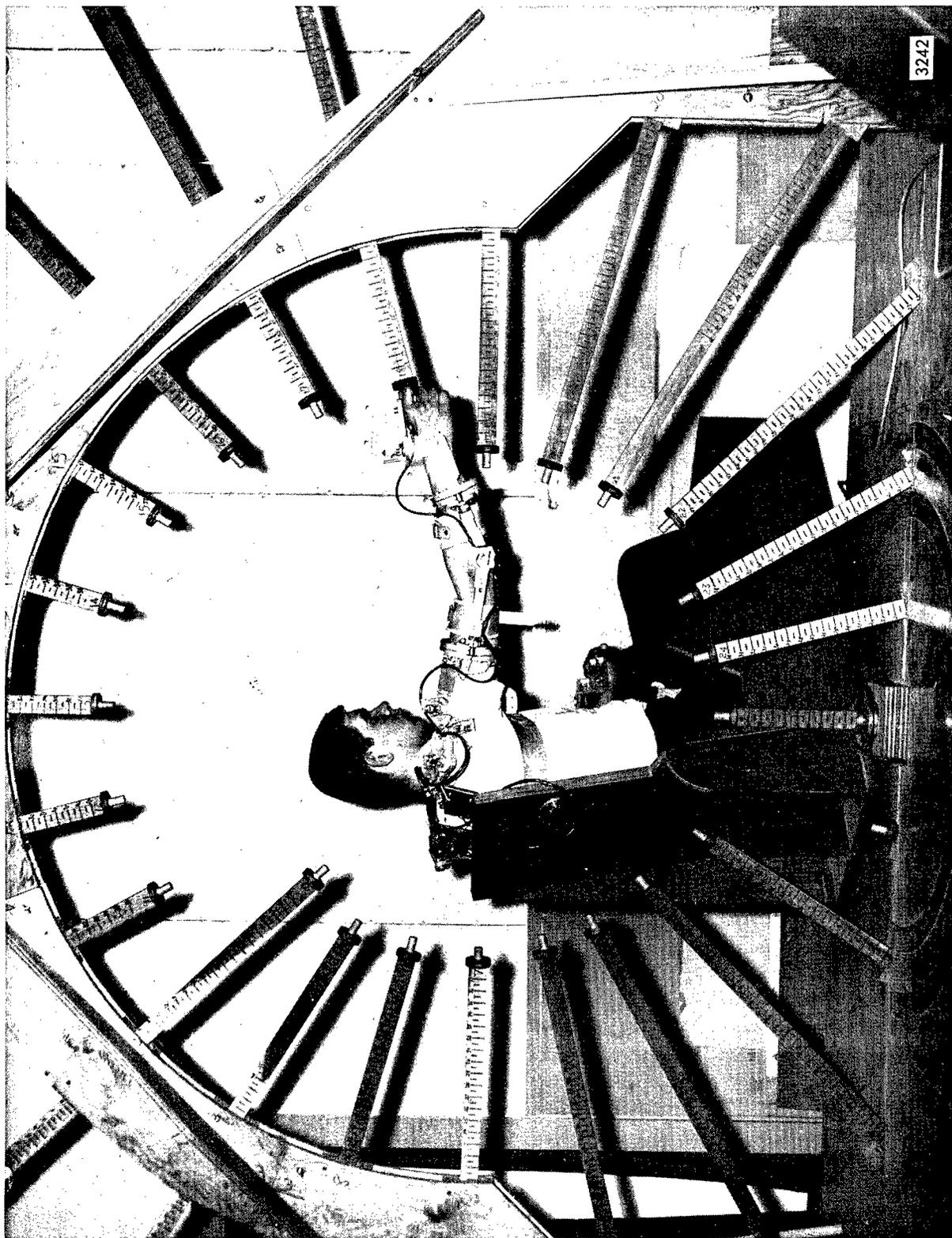
Figure 18   SHOULDER-REACH APPARATUS
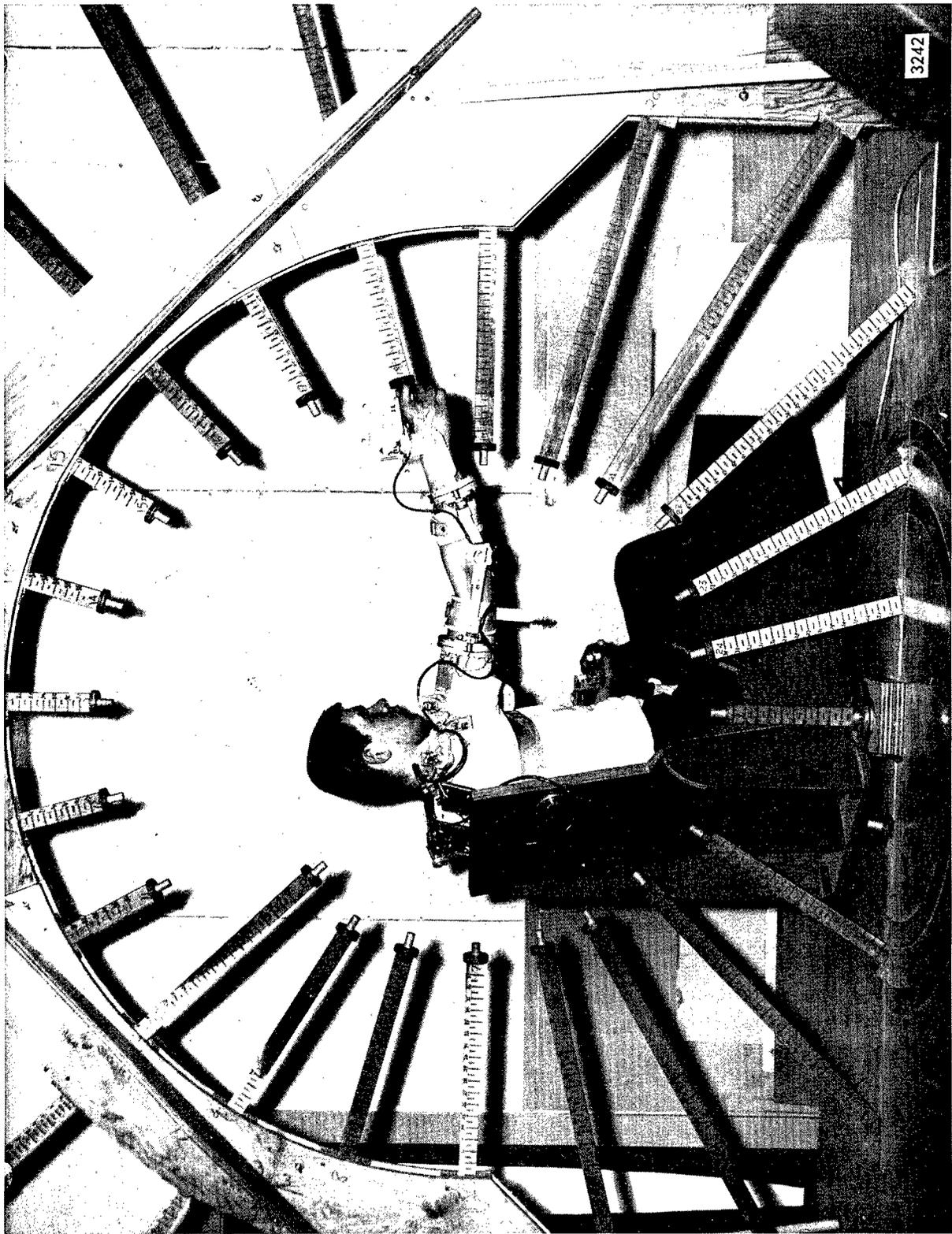
Figure 18 SHOULDER-REACH APPARATUS
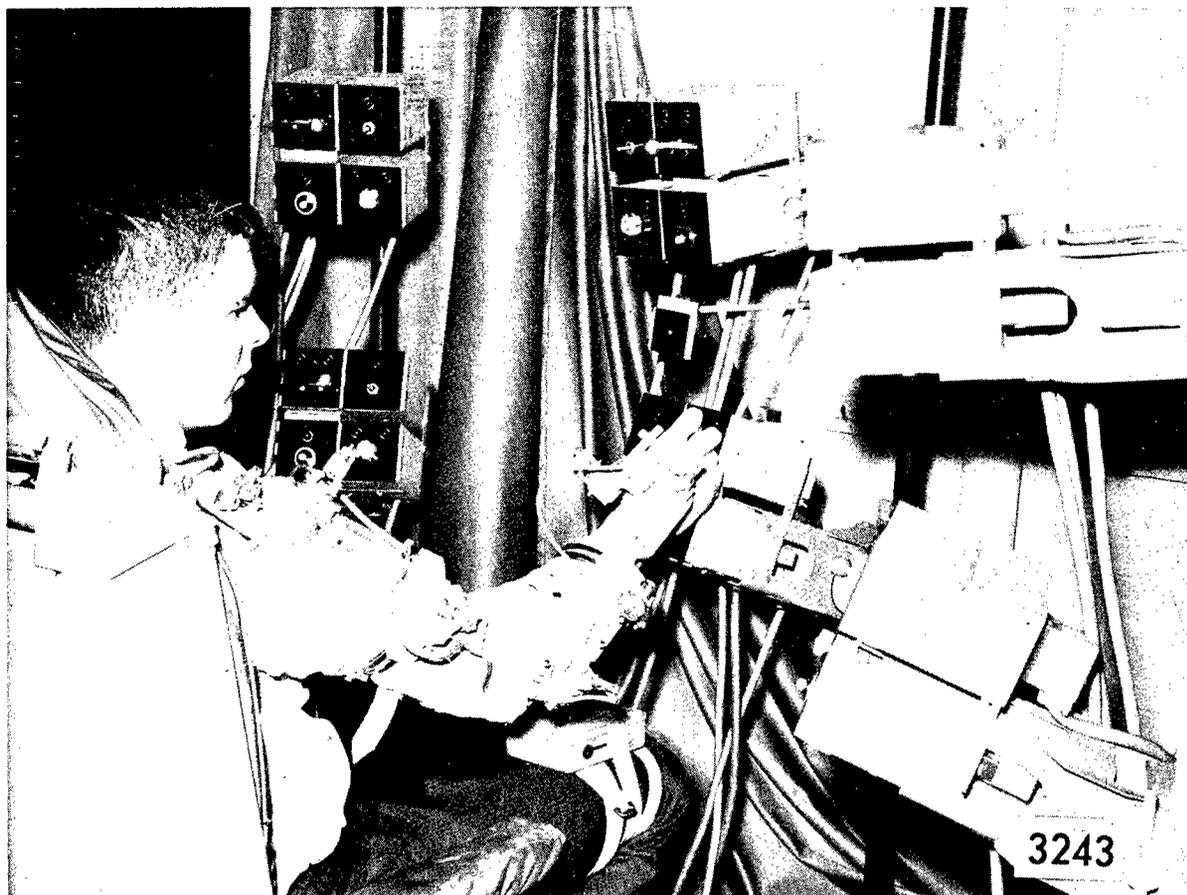
Figure 19   WORK SPACE APPARATUS
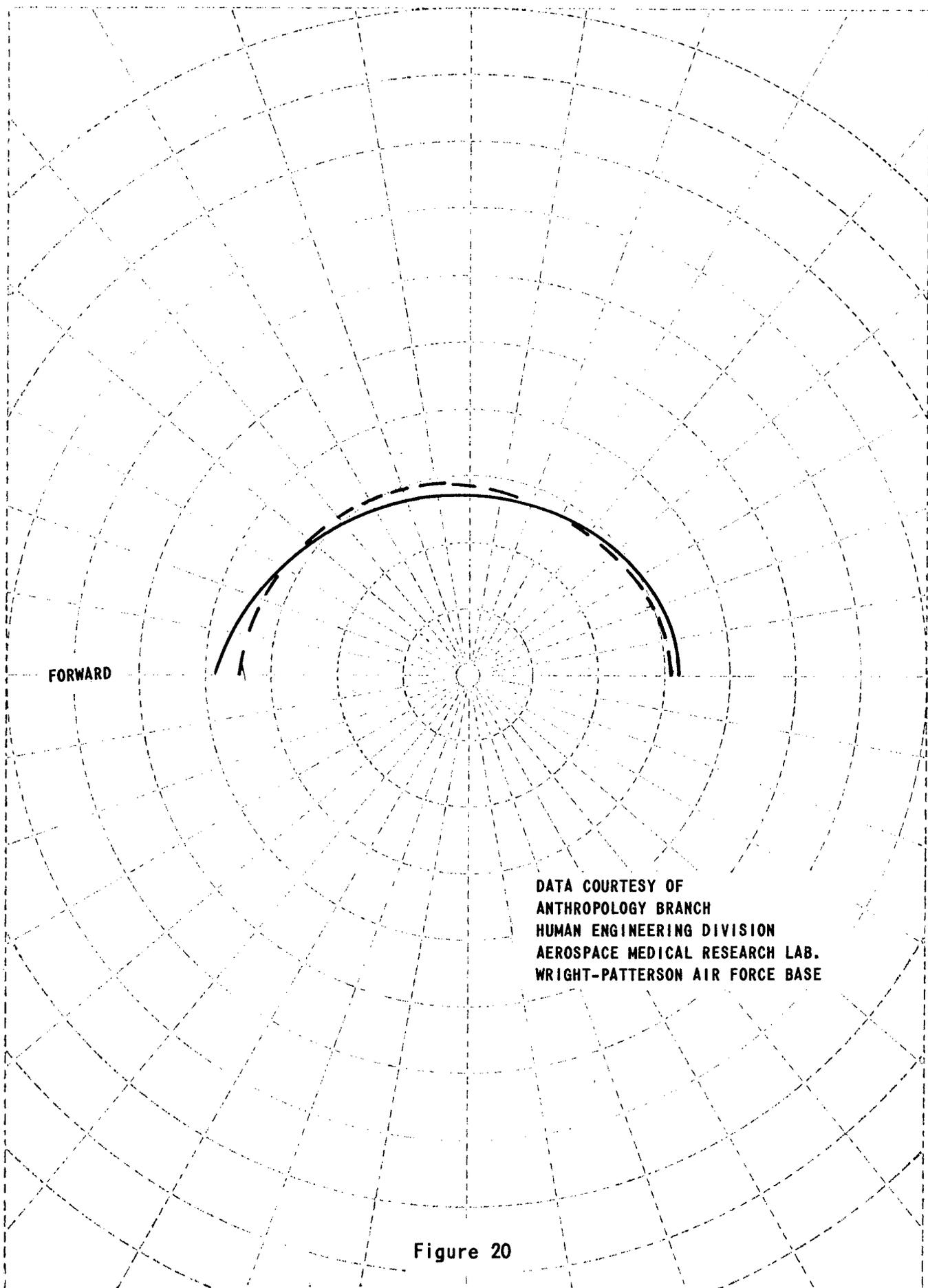
FORWARD

DATA COURTESY OF
ANTHROPOLOGY BRANCH
HUMAN ENGINEERING DIVISION
AEROSPACE MEDICAL RESEARCH LAB.
WRIGHT-PATTERSON AIR FORCE BASE

Figure 20

MAXIMUM REACH OF RIGHT ARM – HORIZONTAL PLANE PASSING THROUGH SEAT REFERENCE POINT

FORWARD

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AEROSPACE MEDICAL RESEARCH LAB.
WRIGHT-PATTERSON AIR FORCE BASE
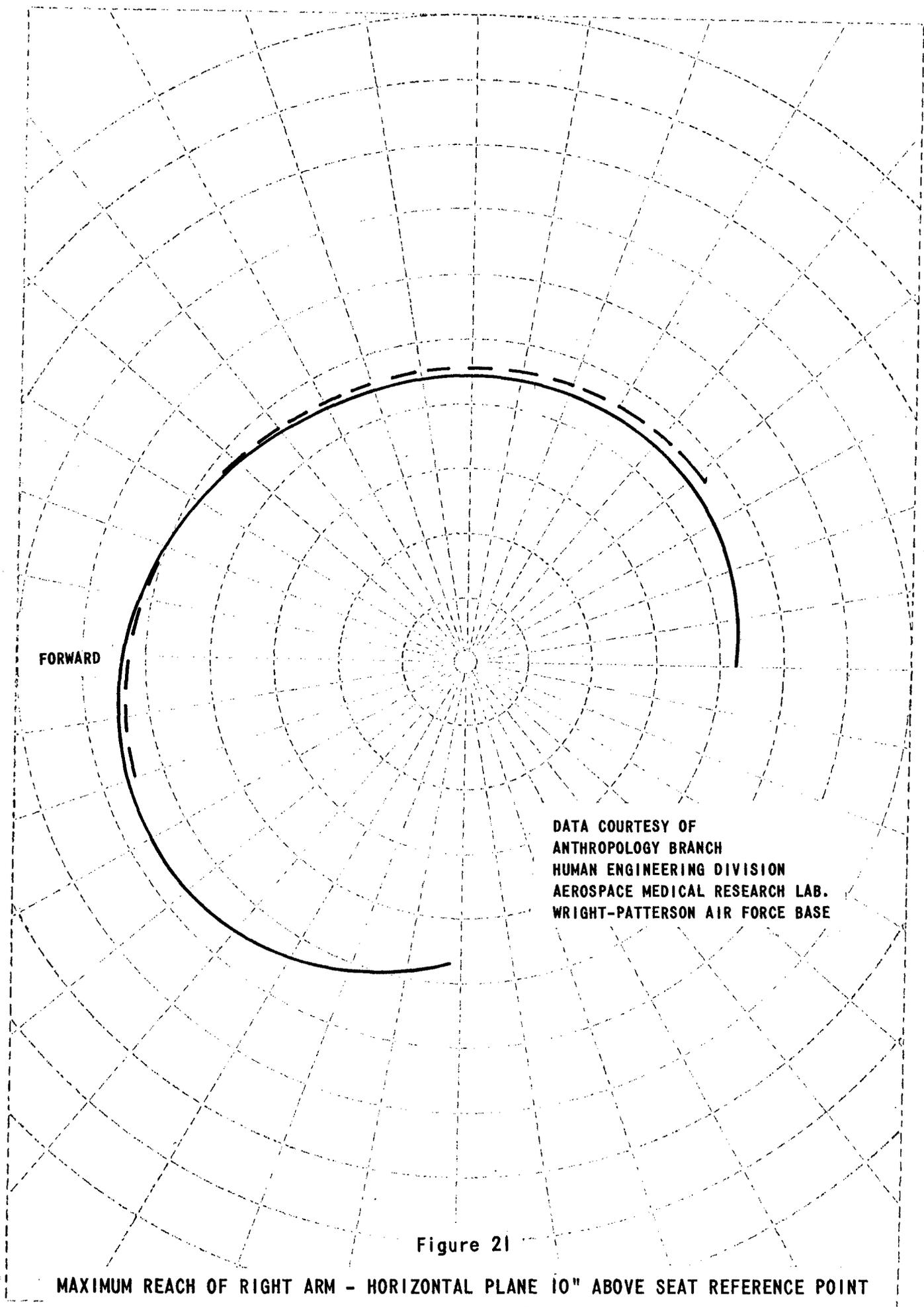
Figure 21

MAXIMUM REACH OF RIGHT ARM - HORIZONTAL PLANE 10" ABOVE SEAT REFERENCE POINT
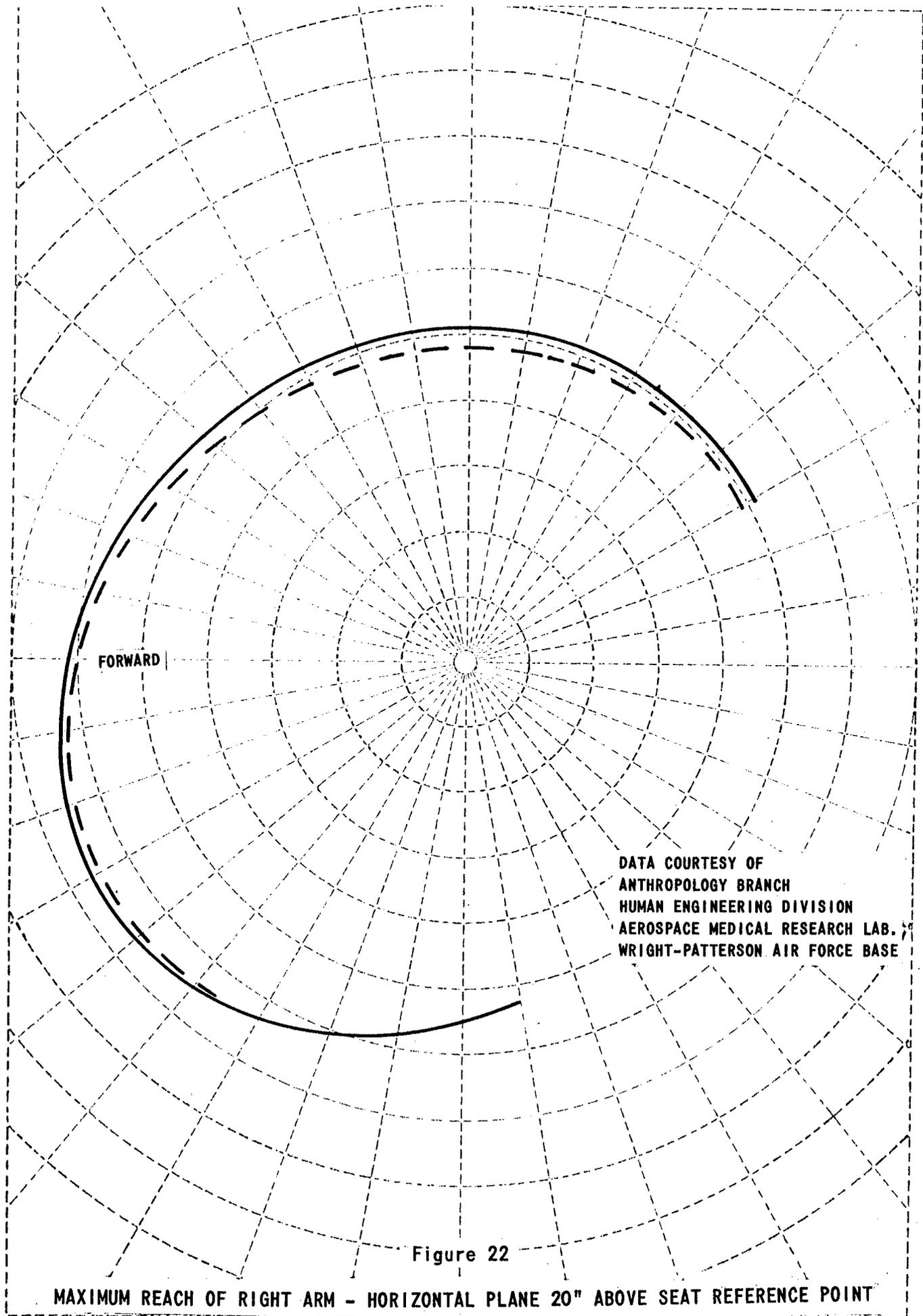
FORWARD

DATA COURTESY OF
ANTHROPOLOGY BRANCH
HUMAN ENGINEERING DIVISION
AEROSPACE MEDICAL RESEARCH LAB.
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Figure 22

MAXIMUM REACH OF RIGHT ARM – HORIZONTAL PLANE 20" ABOVE SEAT REFERENCE POINT

FORWARD

DATA COURTESY OF
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WRIGHT-PATTERSON AIR FORCE BASE
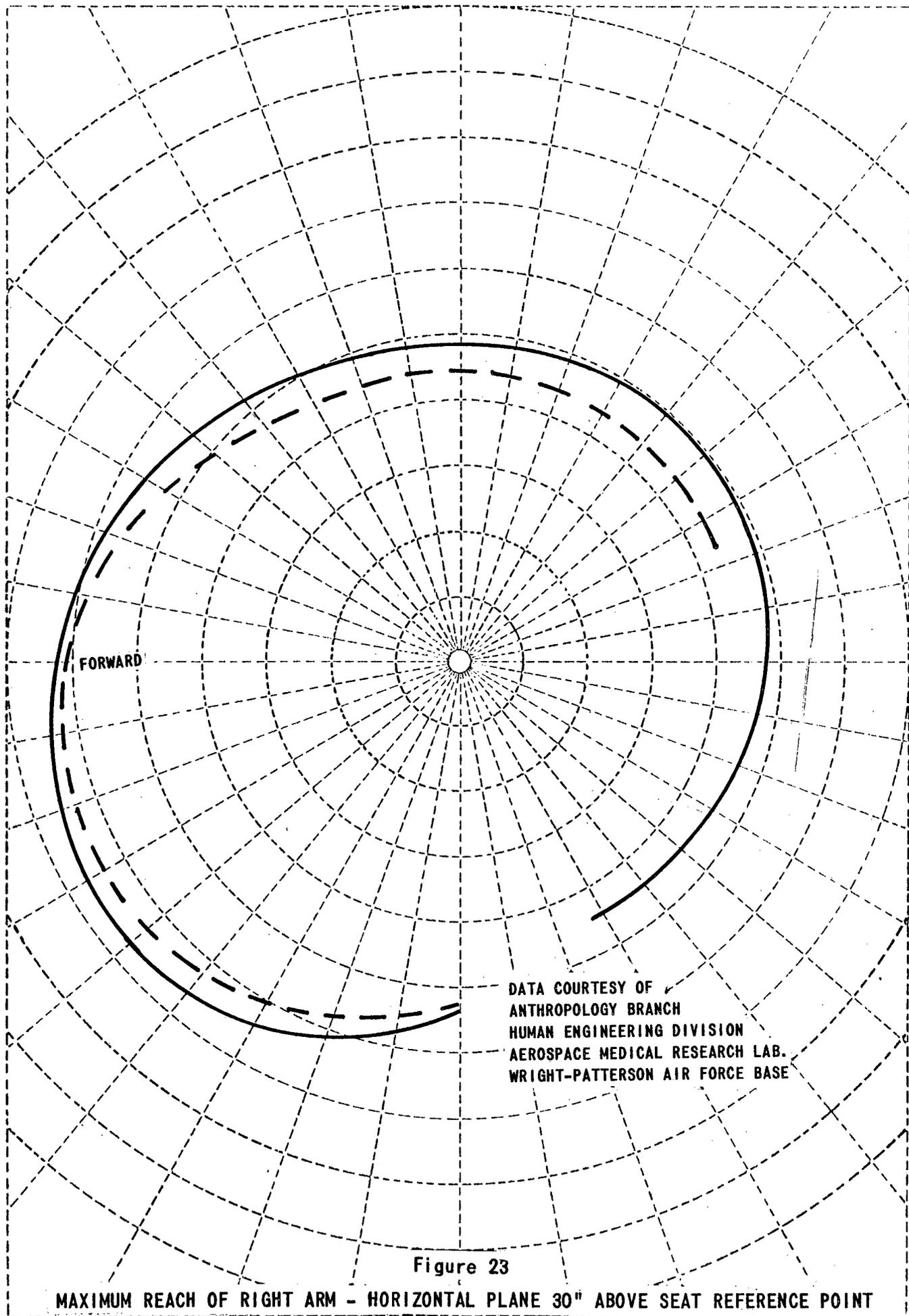
Figure 23

MAXIMUM REACH OF RIGHT ARM - HORIZONTAL PLANE 30" ABOVE SEAT REFERENCE POINT

FORWARD

DATA COURTESY OF
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HUMAN ENGINEERING DIVISION
AEROSPACE MEDICAL RESEARCH LAB.
WRIGHT-PATTERSON AIR FORCE BASE
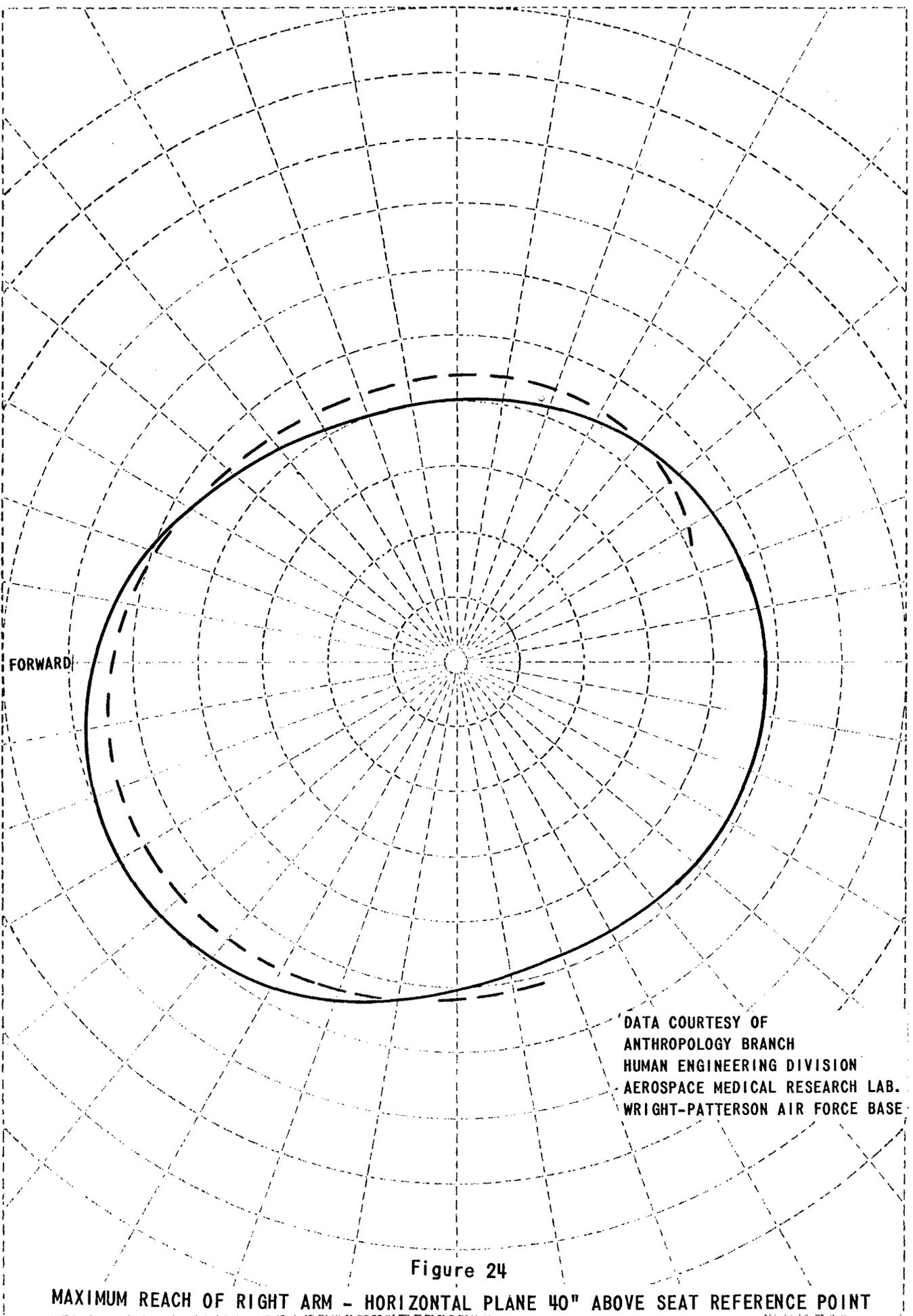
Figure 24
MAXIMUM REACH OF RIGHT ARM - HORIZONTAL PLANE 40" ABOVE SEAT REFERENCE POINT

VO-1692-V-3

FORWARD

DATA COURTESY OF
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HUMAN ENGINEERING DIVISION
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Figure 25
MAXIMUM REACH OF RIGHT ARM — HORIZONTAL PLANE 50" ABOVE SEAT REFERENCE POINT

-41-
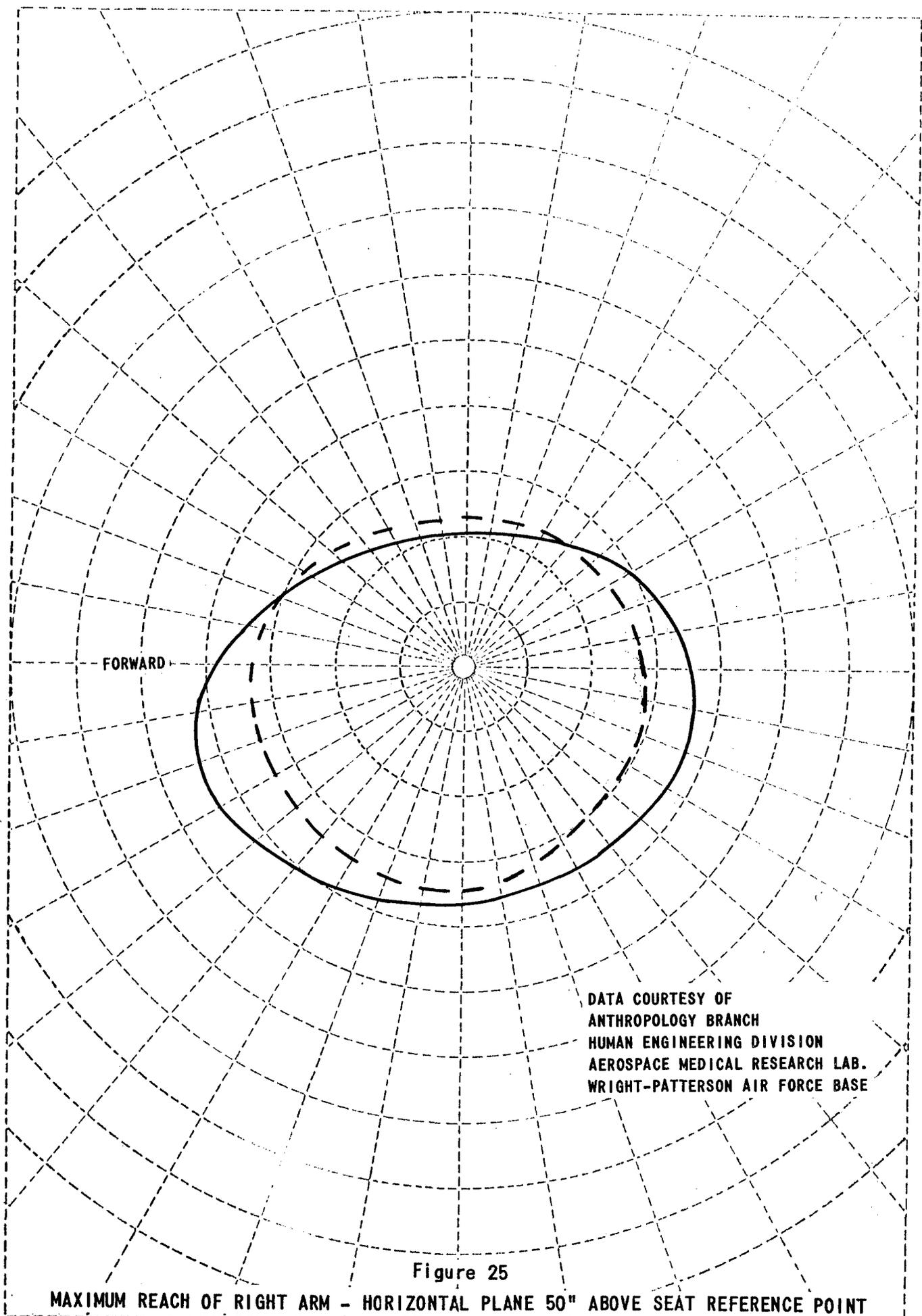
The above noted figures indicate that for certain locations the subject was able to reach further with the exoskeleton than without it. The increase in reach shown is due to inaccuracies in data taking and in data reduction. For such cases, the data presented should be interpreted as no significant difference between reach with and without the exoskeleton. Figures 20 through 25 do show, however, locations that can be reached without the exoskeleton that cannot be reached with the exoskeleton.

3.2.2 Work Space Apparatus[*]

The purpose of the tests performed on the work space apparatus was to determine the effect of the exoskeleton on the ability of the subject to accurately and rapidly position his hands. The tests performed simulated typical control tasks that would be encountered by an astronaut during a space mission. (The test equipment used was constructed to assist in evaluating pressurized space suits.)

The test equipment consisted of control switches that were operated by the subject when he was signaled to do so. Time scores were collected for each operation and the scores were analyzed statistically.

Table 3 shows the console array used in this test. The controls were symmetric around the subject's mid-sagittal plane so that the left half (operated exclusively with the left hand) was a mirror image of the right half (operated exclusively with the right hand). Each half contained four control types (lever, knob, toggle-switch and push-button), and each control type was located in four different positions.

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[*] The work space apparatus was made available through the courtesy of Mr. Earl Sharp, Maintenance Design Branch, Human Engineering Division, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base. Mr. Sharp designed and conducted the experiment and performed the statistical reduction of the raw data.

Table 4 describes each control location in terms of the horizontal distance from a vertical line passing through the seat reference point (the focal distance), the height above the floor, and the angle to the left and right of the subject's mid-sagittal plane (the sagittal angle).

Table 5 shows the order of presentation used. The row marked restriction refers to the two conditions; namely, performance while wearing (W) and performance while not wearing (W/O) the exoskeleton. The hand condition refers to right hand operation (R) or to left hand operation (L). Session 1 was performed in the morning and session 2 was performed the same afternoon. Five operations of each of four controls at each of four locations were presented for each hand condition. Thus there were two sessions, two restriction conditions, two hand conditions, four types of controls, four locations for each type of control for each hand and five replications of each operation making a total of 640 operations in the experiment.

HIGH

							Toggle Switch (TS)	Horiz. Lever (HL)
HL	TS		HL	TS		TS	HL	
PB	K		PB	K		K	PB	Knob (K) · Push Button (PB)

LOW

HL	TS		HL	TS		TS	HL	TS · HL
PB	K		PB	K		K	PB	K · PB

EXTREME	CENTER		CENTER	EXTREME
Left Hand Operation			Right Hand Operation	
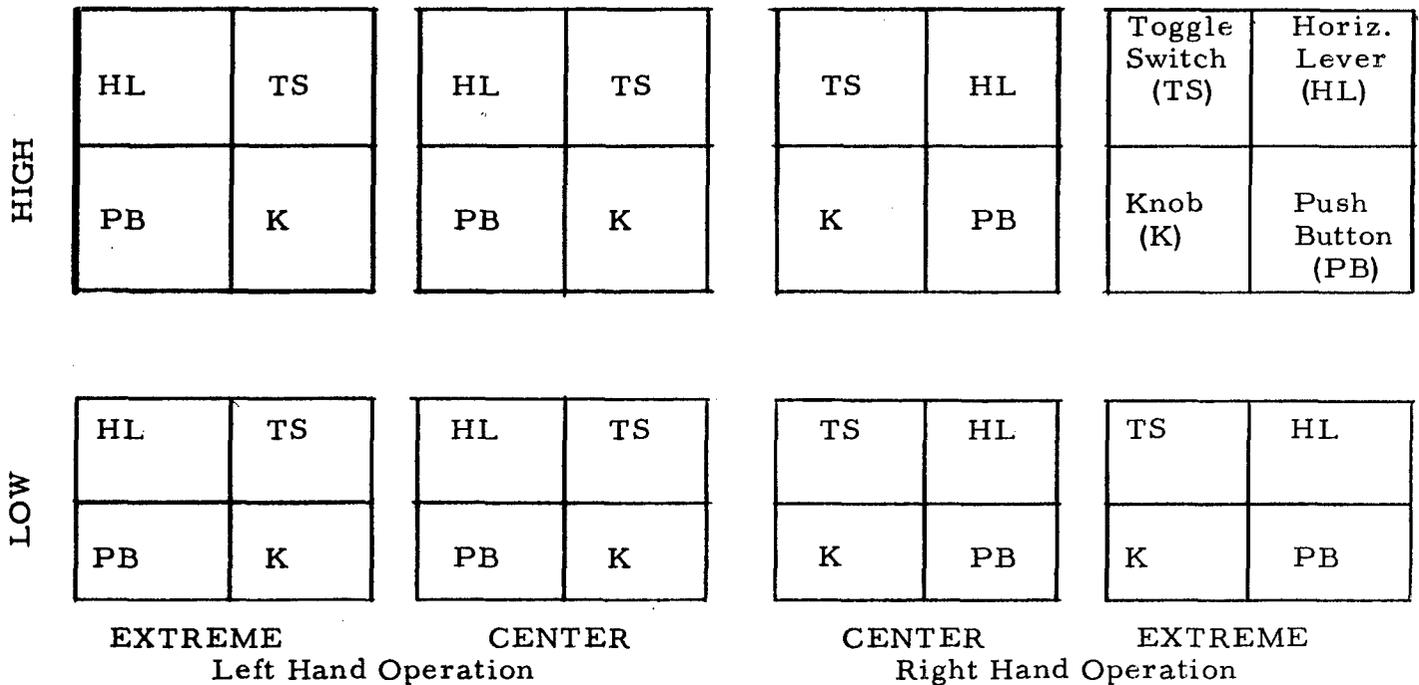
TABLE 3 - DIAGRAM OF CONTROL LAYOUT

		EXTREME			CENTER		
	Control	Focal Distance	Height	Sagittal* Angle (Degrees)	Focal Distance	Height	Sagittal* Angle (Degrees)
LOW	Lever	27-1/8	37-1/4	78°	26-1/8	37-1/4	26°
	Knob	28	34	70°	27	34	17°
	Toggle Switch	27-3/4	37-1/4	70°	26-3/4	37-1/4	17°
	Push Button	27-7/8	33-1/2	78°	26-7/8	33-1/2	26°
HIGH	Lever	24-1/4	49-1/4	78°	23-1/8	49-1/4	26°
	Knob	25	45-3/4	70°	23-7/8	45-3/4	17°
	Toggle Switch	24-3/4	49	70°	23-3/4	49	17°
	Push Button	25	45-3/8	78°	23-3/4	45-3/8	26°

*   Measured in degrees to the right and left of the subject's mid-sagittal plane.

TABLE 4 - MEASUREMENTS DESCRIBING THE SPACIAL
LOCATION OF EACH CONTROL

Session	1				2			
Restriction	W/O		W		W		W/O	
HAND	R	L	L	R	R	L	L	R

TABLE 5 - ORDER OF PRESENTATION

A description of the time scores collected on each control are as follows:

For the Knob and Lever

1.   Reaction Time: The time elapsed from the initial presentation of the light until the subject releases the starting switch.   (Before each test the subject rested his hand on a starting switch at knee level.)

2.   Reach Time: The time elapsed from the release of the starting switch until the subject touches the control.

3.   Manipulation Time:[*]   The time elapsed from the touching of the control until the null region is first entered.

4.   Adjustment Time:[*]   The time taken to reposition the knob within the null region in the event that the null region is passed.

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[*]   Before each test run the knobs and levers were positioned against an internal stop.   The subject was signalled to operate each control by a light which was extinguished when the control was operated correctly. For the lever and knob, if the subject passed the control through the correct or null setting, the light continued to glow until the control was relocated correctly.

For the Toggle Switch and Push-Button

1.   Reaction Time: The time elapsed from the initial presentation of the light until the subject releases the starting switch.

2.   Operation Time: The time elapsed from the release of the ready switch until the light is extinguished.

Table 6 contains mean scores and standard deviations for each condition based on the ten replications of each control-hand-location-restriction combination. Analyses of variance were run for each control type, and for various components of the total response time. The following statistical inferences at the 0.95 level of confidence were thereby obtained:

A.   Lever

  1. Reaction Time

      a)   Reaction time is less with the exoskeleton than without.

      b)   Reaction time is less with the left hand than with the right.

  2. Reach Time

      a)   Reach time is less without the exoskeleton.

      b)   There is a statistically significant difference in reach time between locations.

      c)   Reach time is less for the right hand than for the left hand.

TABLE 6

MEAN SCORES AND STANDARD DEVIATIONS

Item	Hand	Location	Reaction Restriction Without X̄	SD	Reaction With X̄	SD	Reach Restriction Without X̄	SD	Reach With X̄	SD	Manipulation Restriction Without X̄	SD	Manipulation With X̄	SD	Adjustment Restriction Without X̄	SD	Adjustment With X̄	SD	Manipulation Adjustment Without X̄	SD	Manip. Adj. With X̄	SD	Total Restriction Without X̄	SD	Total With X̄	SD
Lever	Right Hand	1	.41	.06	.33	.02	.66	.13	.62	.09	.52	.32	.54	.23	.58	.56	.38	.30	1.10	.47	.92	.20	2.17	.51	1.87	.20
Lever	Right Hand	2	.45	.15	.34	.04	.60	.12	.70	.11	.51	.36	.48	.29	.30	.31	.51	.42	.81	.36	.99	.37	1.86	.41	2.04	.37
Lever	Right Hand	3	.38	.05	.38	.04	.48	.07	.52	.11	.52	.23	.69	.29	.19	.33	.25	.44	.72	.39	.94	.32	1.57	.42	1.83	.32
Lever	Right Hand	4	.40	.04	.35	.02	.56	.07	.61	.08	.65	.36	.53	.40	.33	.40	.70	.50	.98	.29	1.22	.34	1.94	.31	2.18	.36
Lever	Left Hand	1	.35	.07	.32	.02	.67	.18	.74	.09	.77	.39	.97	.61	.28	.40	.52	.61	1.04	.34	1.49	.74	2.06	.35	2.55	.76
Lever	Left Hand	2	.38	.07	.31	.03	.68	.12	.83	.12	.54	.31	.70	.35	.26	.38	.52	.76	.80	.23	1.22	.54	1.86	.30	2.35	.53
Lever	Left Hand	3	.38	.06	.33	.04	.53	.14	.55	.10	.50	.27	.60	.40	.16	.20	.36	.35	.66	.36	.96	.34	1.56	.44	1.83	.39
Lever	Left Hand	4	.38	.06	.34	.05	.54	.12	.72	.10	.43	.17	.51	.30	.37	.47	.62	.84	.80	.49	1.12	.71	1.72	.49	2.19	.71
Knob	Right Hand	1	.43	.08	.33	.04	.61	.09	.60	.12	.98	.39	.72	.34	.46	.36	.44	.47	1.44	.49	1.16	.63	2.48	.53	2.09	.69
Knob	Right Hand	2	.41	.07	.35	.08	.61	.12	.60	.09	.81	.33	.70	.49	.47	.37	.46	.29	1.28	.37	1.15	.57	2.29	.44	2.11	.61
Knob	Right Hand	3	.41	.04	.34	.03	.53	.06	.51	.10	.87	.57	.90	.67	.56	.54	.42	.35	1.43	.62	1.32	.49	2.36	.62	2.19	.46
Knob	Right Hand	4	.43	.08	.34	.03	.58	.09	.58	.08	.63	.34	.50	.28	.55	.42	.31	.31	1.19	.44	.81	.26	2.19	.45	1.73	.28
Knob	Left Hand	1	.38	.08	.31	.03	.61	.17	.63	.06	.96	.51	.79	.14	.40	.45	.30	.19	1.37	.55	1.10	.19	2.36	.59	2.04	.18
Knob	Left Hand	2	.40	.06	.33	.05	.65	.15	.73	.12	.57	.29	.55	.19	.46	.44	.49	.27	1.03	.41	1.04	.20	2.08	.56	2.09	.31
Knob	Left Hand	3	.38	.05	.34	.05	.44	.09	.51	.08	.56	.22	.81	.34	.22	.25	.42	.24	.77	.28	1.23	.41	1.59	.71	2.07	.45
Knob	Left Hand	4	.38	.06	.32	.03	.50	.09	.64	.08	.84	.62	.85	.28	.37	.36	.41	.27	1.21	.65	1.26	.34	2.09	.71	2.21	.37
Toggle Switch	Right Hand	1	.52	.09	.47	.08					.65	.09	.71	.23									1.17	.15	1.17	.29
Toggle Switch	Right Hand	2	.54	.11	.51	.07					.71	.18	.76	.13									1.24	.21	1.27	.12
Toggle Switch	Right Hand	3	.50	.09	.45	.11					.56	.09	.51	.14									1.05	.14	.96	.17
Toggle Switch	Right Hand	4	.55	.08	.47	.11					.65	.18	.55	.12									1.20	.17	1.02	.20
Toggle Switch	Left Hand	1	.60	.21	.46	.10					.64	.09	.83	.12									1.24	.26	1.28	.13
Toggle Switch	Left Hand	2	.50	.06	.45	.10					.62	.09	1.25	1.29									1.11	.13	1.71	1.25
Toggle Switch	Left Hand	3	.54	.10	.51	.10					.59	.30	.61	.17									1.13	.11	1.12	.22
Toggle Switch	Left Hand	4	.54	.10	.49	.10					.54	.11	.69	.09									1.08	.10	1.18	.13
Push Button	Right Hand	1	.57	.14	.50	.08					.63	.13	.72	.11									1.19	.19	1.22	.16
Push Button	Right Hand	2	.62	.30	.42	.11					.63	.10	.71	.22									1.25	.31	1.14	.29
Push Button	Right Hand	3	.57	.13	.48	.09					.59	.19	.57	.15									1.15	.19	1.06	.18
Push Button	Right Hand	4	.51	.09	.49	.07					.55	.15	.64	.17									1.06	.23	1.14	.21
Push Button	Left Hand	1	.47	.06	.52	.09					.67	.16	1.03	.18									1.14	.19	1.55	.19
Push Button	Left Hand	2	.60	.25	.46	.09					.67	.13	.89	.23									1.27	.27	1.34	.28
Push Button	Left Hand	3	.58	.11	.48	.11					.44	.08	.61	.12									1.02	.12	1.08	.15
Push Button	Left Hand	4	.50	.10	.44	.08					.62	.37	.71	.14									1.12	.40	1.16	.18

NO SCORES COLLECTED (Reach, Adjustment, and Manipulation Adjustment for Toggle Switch and Push Button)

(See Note Below)

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THE ENCLOSED BLOCK ABOVE IS, AS DEFINED IN THE TEXT, OPERATION TIME

3. Manipulation Time

    a) There is no statistically significant difference between manipulation time with the exoskeleton and manipulation time without the exoskeleton.

    b) There is an interaction between hand and location for manipulation time. In other words, the difference in manipulation time between the two hands depends on the location involved.

4. Adjustment Time

    a) Adjustment time is less without the exoskeleton.

5. Manipulation Plus Adjustment Time

    a) Manipulation plus adjustive is less without the exoskeleton.

    b) The difference in manipulation plus adjustment time with and without the exoskeleton depends upon the location of the lever.

6. Total Time

    a) The total time to control the lever is less without the exoskeleton than with the exoskeleton.

    b) The total time for the left hand is increased by the exoskeleton more than for the right hand.

B. Knob

1. Reaction Time

    a) Reaction time is less with the exoskeleton.

    b) Reaction time is less for the right hand than for the left hand.

2. Reach Time

a) Reach time is less without the exoskeleton.

b) Reach time varies significantly with different knob locations.

c) For reach time, the left hand is hampered more by the exoskeleton than the right hand.

d) The differences in reach time between the two hands depends upon the location of the knob.

3. Manipulation Time

a) There is no statistically significant difference in manipulation time with and without the exoskeleton.

4. Adjustment Time

a) There is no statistically significant difference in adjustment time with and without the exoskeleton.

5. Manipulation Plus Adjustment Time

a) There is no statistically significant difference in manipulation plus adjustment time with and without the exoskeleton.

6. Total Time

a) There is no statistically significant difference in total time with and without the exoskeleton.

b) For total time, the left hand is hampered more than the right hand by the exoskeleton.

c) The left hand is faster at certain locations of the knob than at other locations.

C.   Toggle Switch

    1.   Reaction Time

        a)   Reaction time is less with the exoskeleton.

        b)   Reaction time does not vary significantly with different hands or locations.

    2.   Operation Time

        a)   Operation time is less without the exoskeleton.

        b)   Operation time varies at different locations. Position 3 requires the least operation time and position 2 requires the most.

        c)   Operation time with the exoskeleton is greater for the left hand than for the right. Thus, the left hand is hampered more than the right hand.

    3.   Total Time

        a)   The exoskeleton does not significantly effect total time.

        b)   Certain locations require less total time than others. Location 3 requires the most time, 2 the least.

        c)   The left hand requires more time than the right hand, when the exoskeleton is used.

D.   Push-Button

    1.   Reaction Time

        a)   Reaction time is less with the exoskeleton.

    2.   Operation Time

        a)   Operation time is less without the exoskeleton.

        b)   Certain locations require less operation time than others. Location 3 requires the least time and location 1 the most.

c) The right hand requires less operation time than the left.

d) When the exoskeleton is used, the operation time for the right hand is less than for the left hand. Thus, the left hand is hampered by the exoskeleton more than the right hand.

3. Total Time

a) Certain locations require more time than others. Location 1 requires the most time, location 3 the least.

For all of the above tests the reaction time is less with the exoskeleton than without it. It is postulated that the decrease in reaction time was caused largely by motivation of the subject. The test equipment had a noise pattern that enabled him to predict the signal light (but not predict the particular control that would be operated).

3.2.3 Recordings of Positions of Exoskeletal Joints

In order to determine motion of the exoskeleton during shoulder and arm movement of the subject, the position of the exoskeletal joints as a function of time was recorded for certain shoulder and arm movements. Movements chosen were: shoulder movement in the transverse plane (abduction, adduction and sideward elevation), shoulder movement in a plane 45 degrees to the right of the sagittal plane, shoulder movement in the sagittal plane (flexion, extension, forward elevation and hyperextension), shoulder movement in a plane 45 degrees to the left of the sagittal plane, internal and external rotation of the shoulder, and elbow flexion and extension. Motion of the right shoulder only was recorded.

Figures 26 through 31 present motion of exoskeletal shoulder joints during movements discussed above. The exoskeletal joint numbers shown in Figures 26 through 31 refer to Figure 32. The abscissa in Figures 26 through 31 is a percentage of the completed motion. For Figure 26 the compiled motion recorded consists of starting from the neutral position and raising the arm sidewards as high as possible and returning to the neutral position. For Figures 27 through 29, the motion recorded consists of starting from the neutral position and bringing the arm forward until the arm is vertical above the shoulder, and then returning to the neutral position from behind the transverse plane. Motion recorded in Figure 30 consists of flexing the elbow approximately 90 degrees and holding the upper arm in extreme external rotation, and rotating the upper arm to extreme internal rotation and returning to rest. Motion recorded in Figure 31 consists of starting with the elbow held straight and flexing the elbow as far as possible and returning to original position.

In order to evaluate the motion range, velocity and acceleration of exoskeletal joints for the upper extremity, the position of upper extremity exoskeletal joints was recorded continuously with time during typical shoulder-arm and wrist movements. It had been concluded earlier that wrist flexion-extension and wrist ulnar-radial rotation were not required to perform the selected tasks, and consequently exoskeletal joints that permit these motions were locked out. No specific work task was performed during the above measurements; rather, the subject moved his arms in general motion patterns, with joint velocity of a magnitude that would be normally used during work tasks.
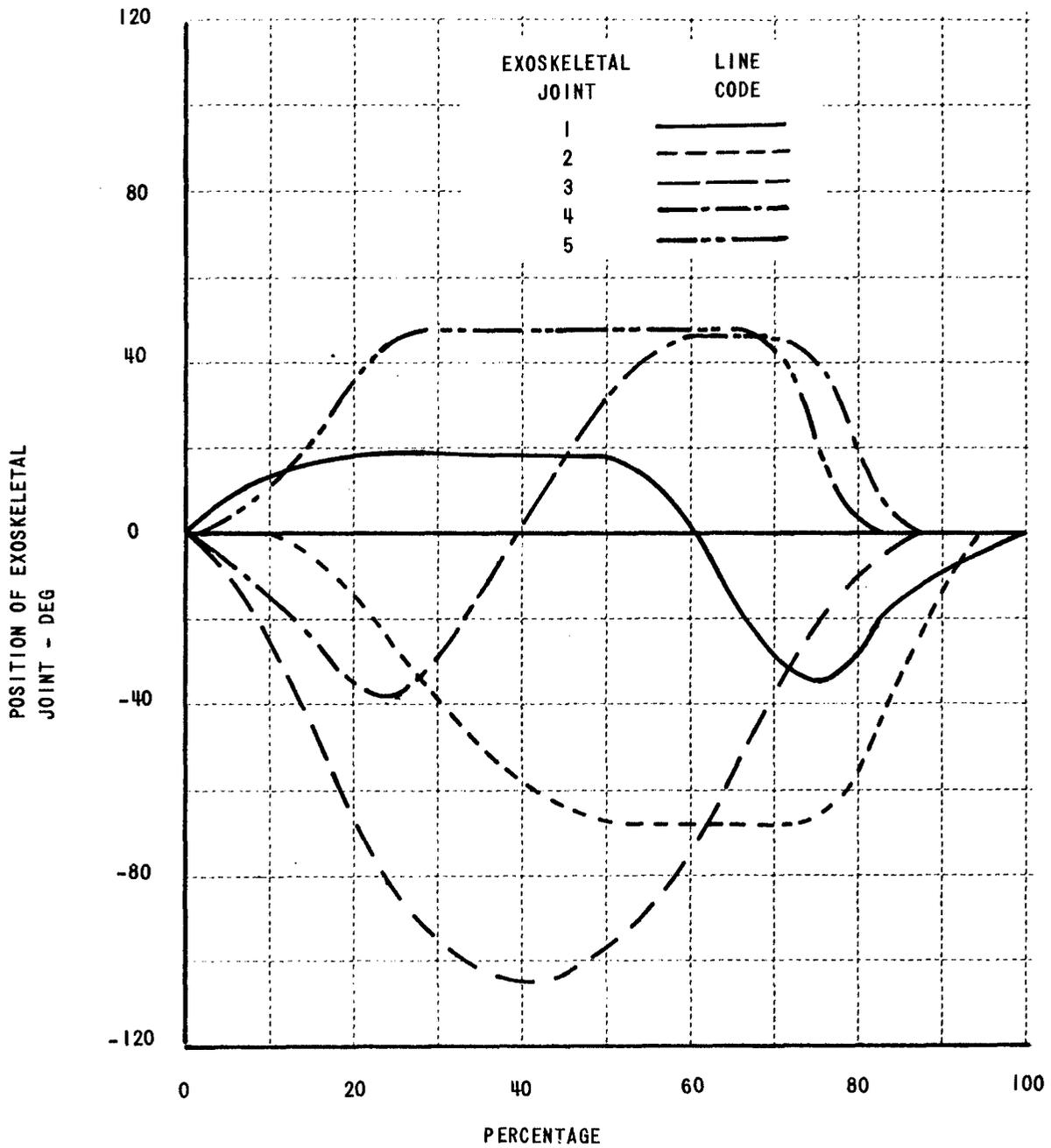
Figure 26

TIME HISTORY OF EXOSKELETAL SHOULDER JOINTS DURING MOTION
IN THE TRANSVERSE PLANE

VO-1692-V-3
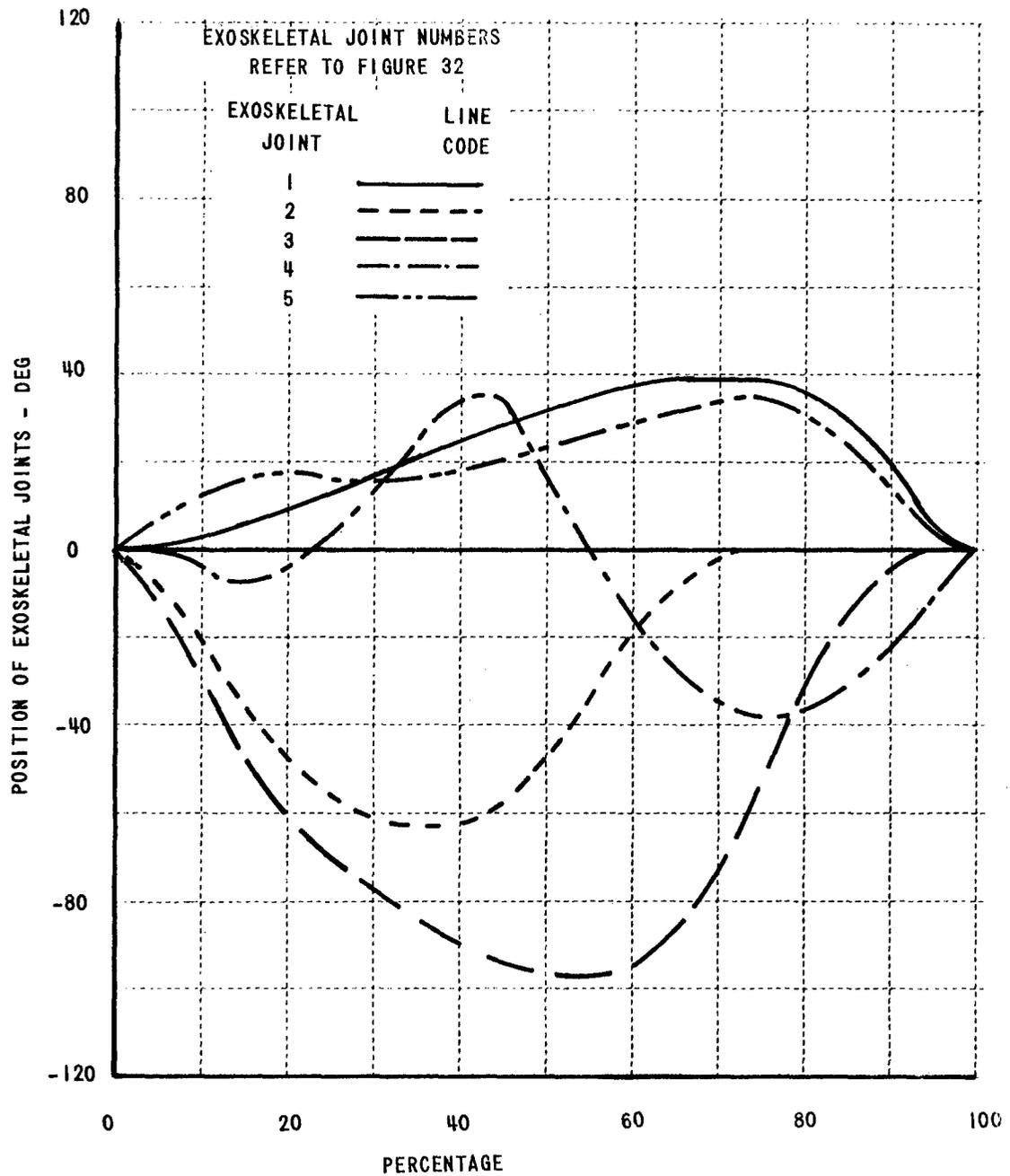
Figure 27

TIME HISTORY OF EXOSKELETAL SHOULDER JOINTS DURING MOTION IN A
PLANE 45° IN FRONT OF THE RIGHTWARD TRANSVERSE PLANE
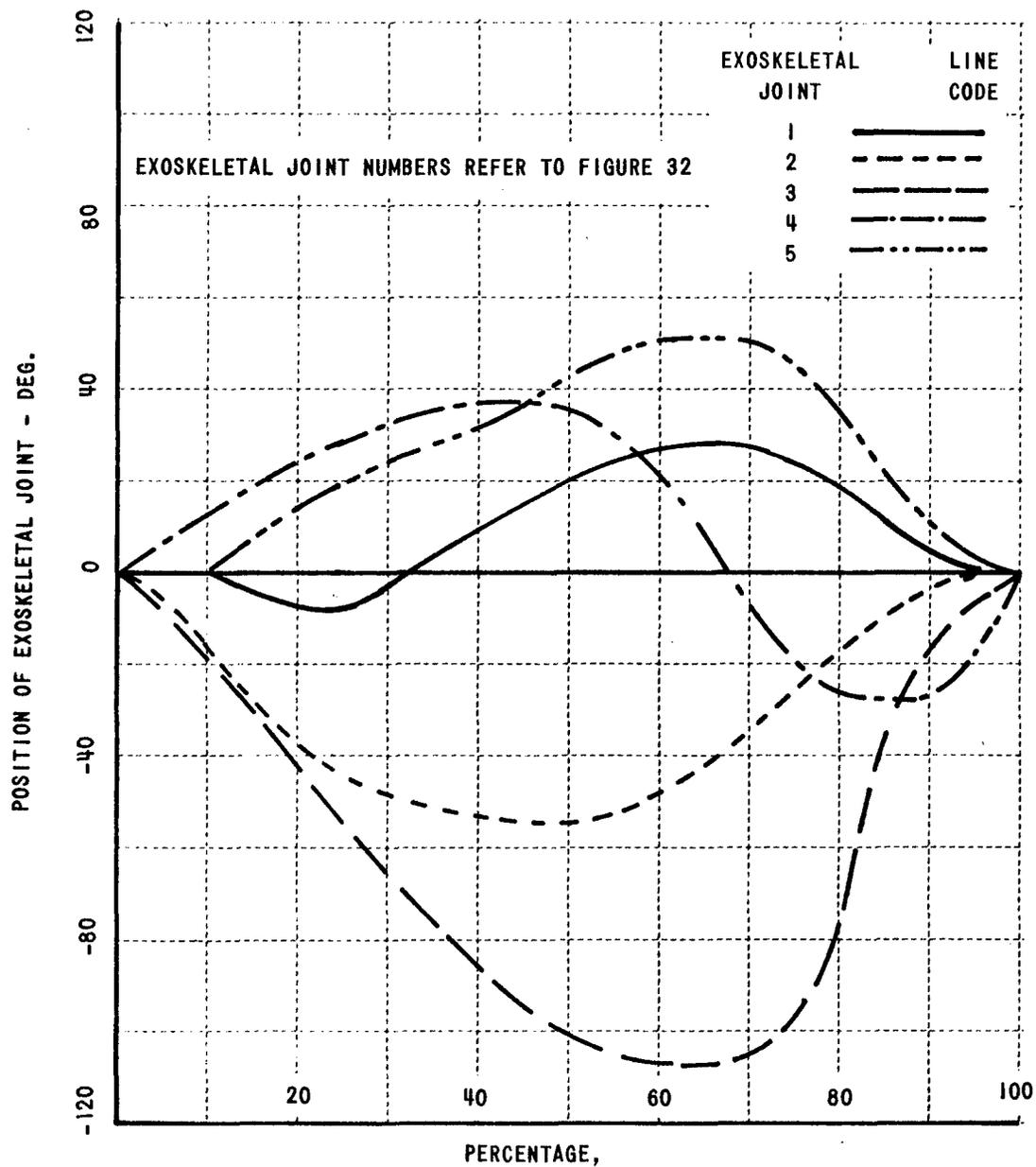
Figure 28

TIME HISTORY OF EXOSKELETAL SHOULDER JOINTS

DURING MOTION IN THE SAGITTAL PLANE
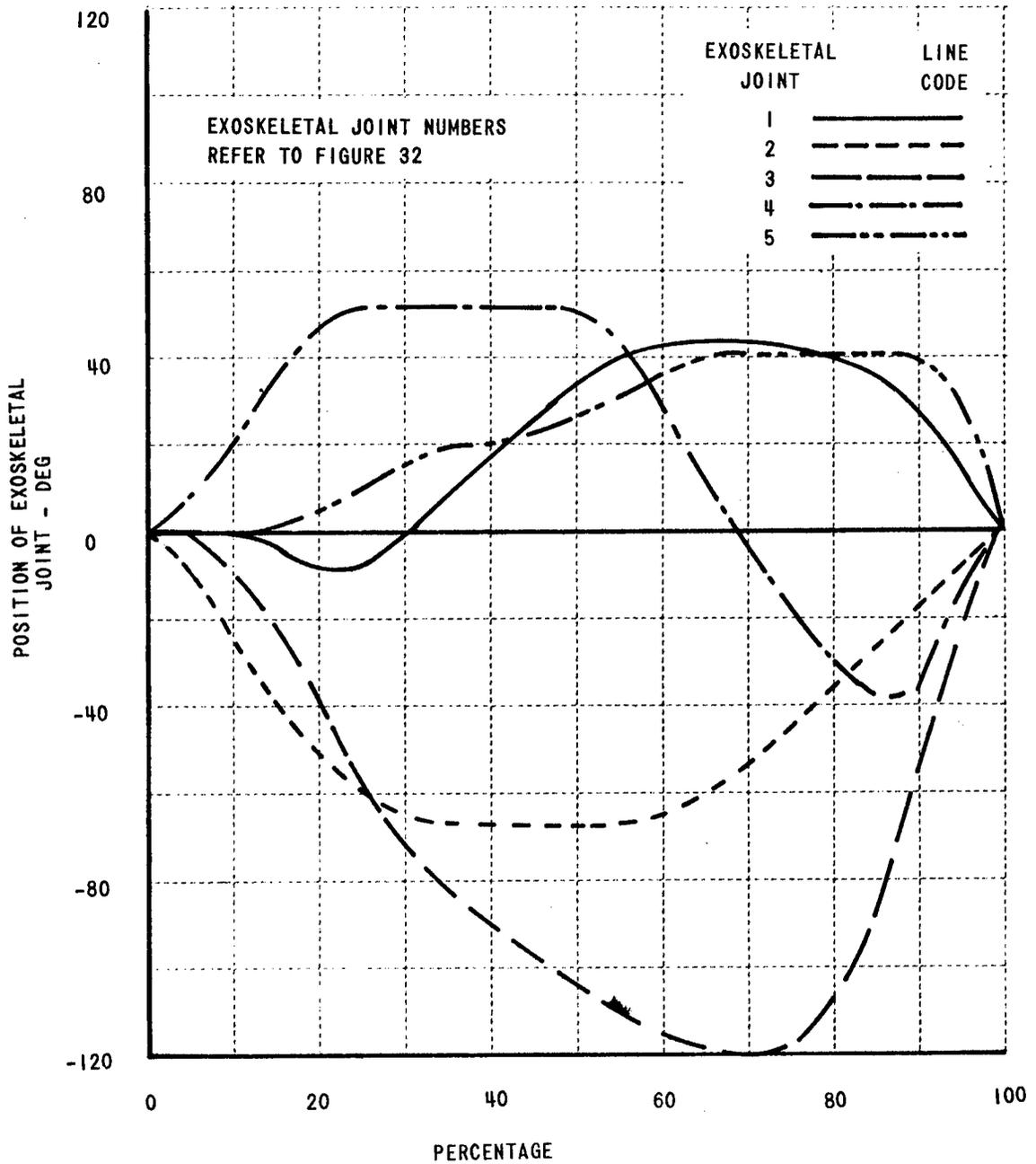
Figure 29

TIME HISTORY OF EXOSKELETAL SHOULDER JOINTS DURING MOTION
IN A PLANE 45° IN FRONT OF THE LEFTWARD TRANSVERSE PLANE

EXOSKELETAL JOINT NUMBER 5
FIGURE 32
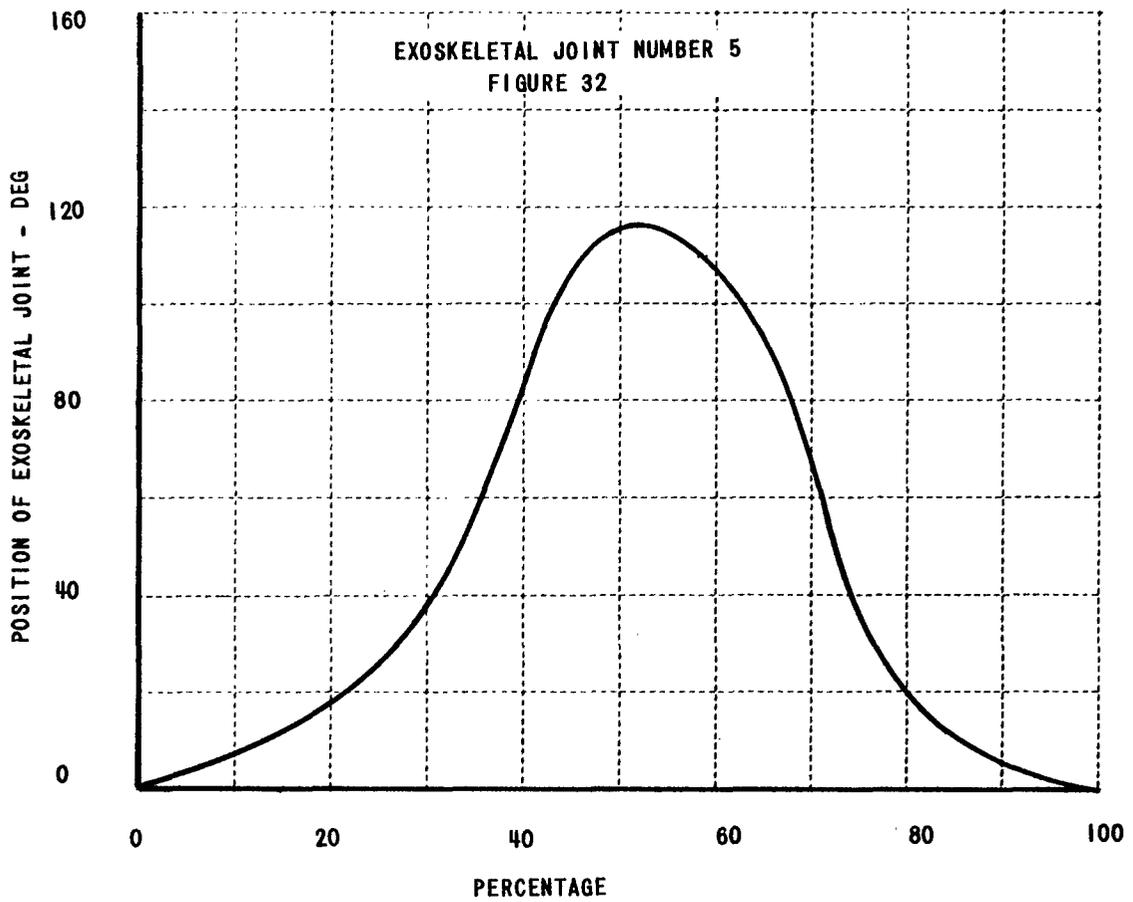
Figure 30

TIME HISTORY OF EXOSKELETAL SHOULDER JOINT DURING INTERNAL AND
EXTERNAL SHOULDER ROTATION
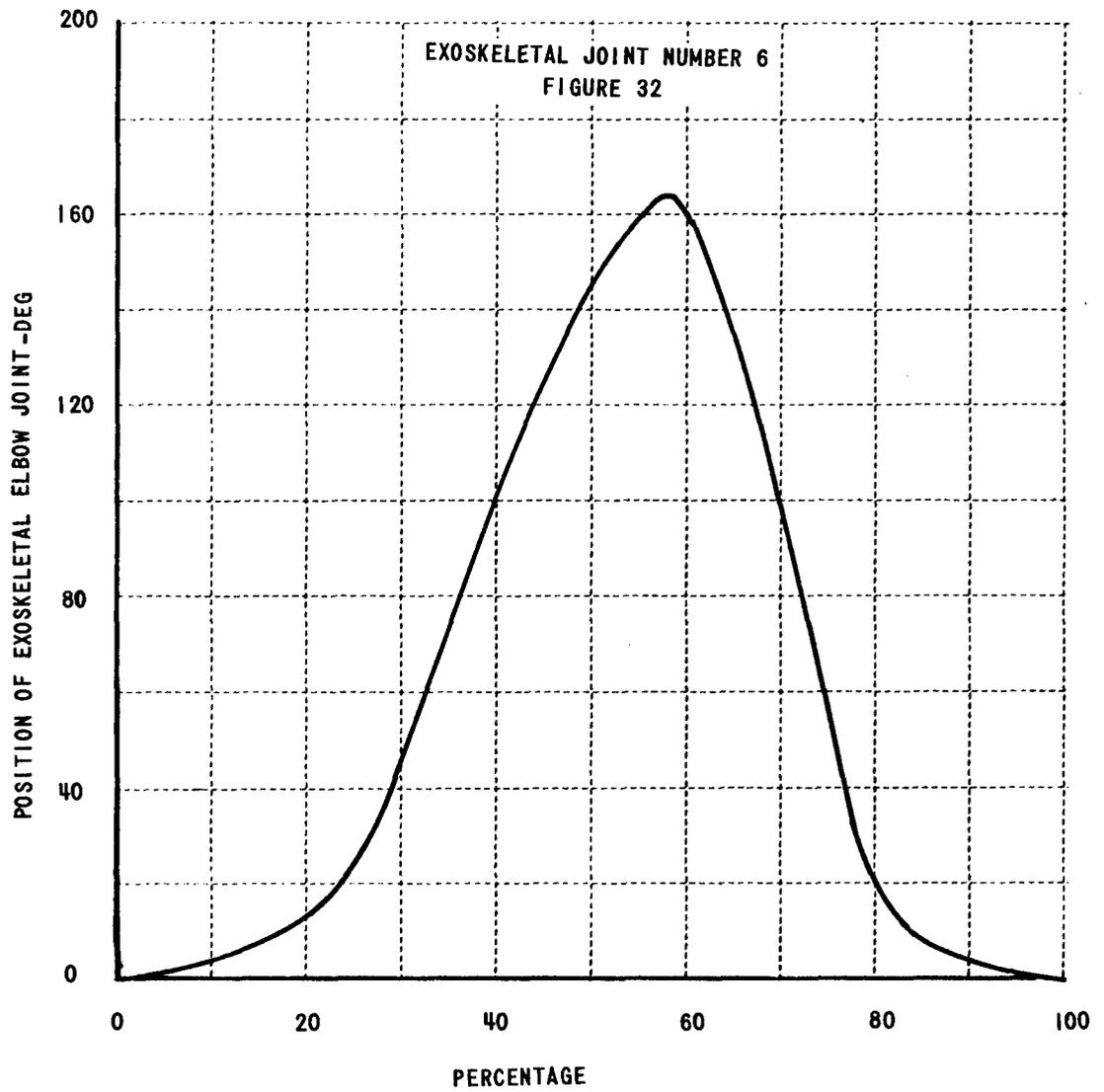
Figure 31

TIME HISTORY OF EXOSKELETAL JOINT DURING
FLEXION AND EXTENSION OF ELBOW

Figure 32   EXOSKELETAL JOINT NUMBERS - UPPER EXTREMITY
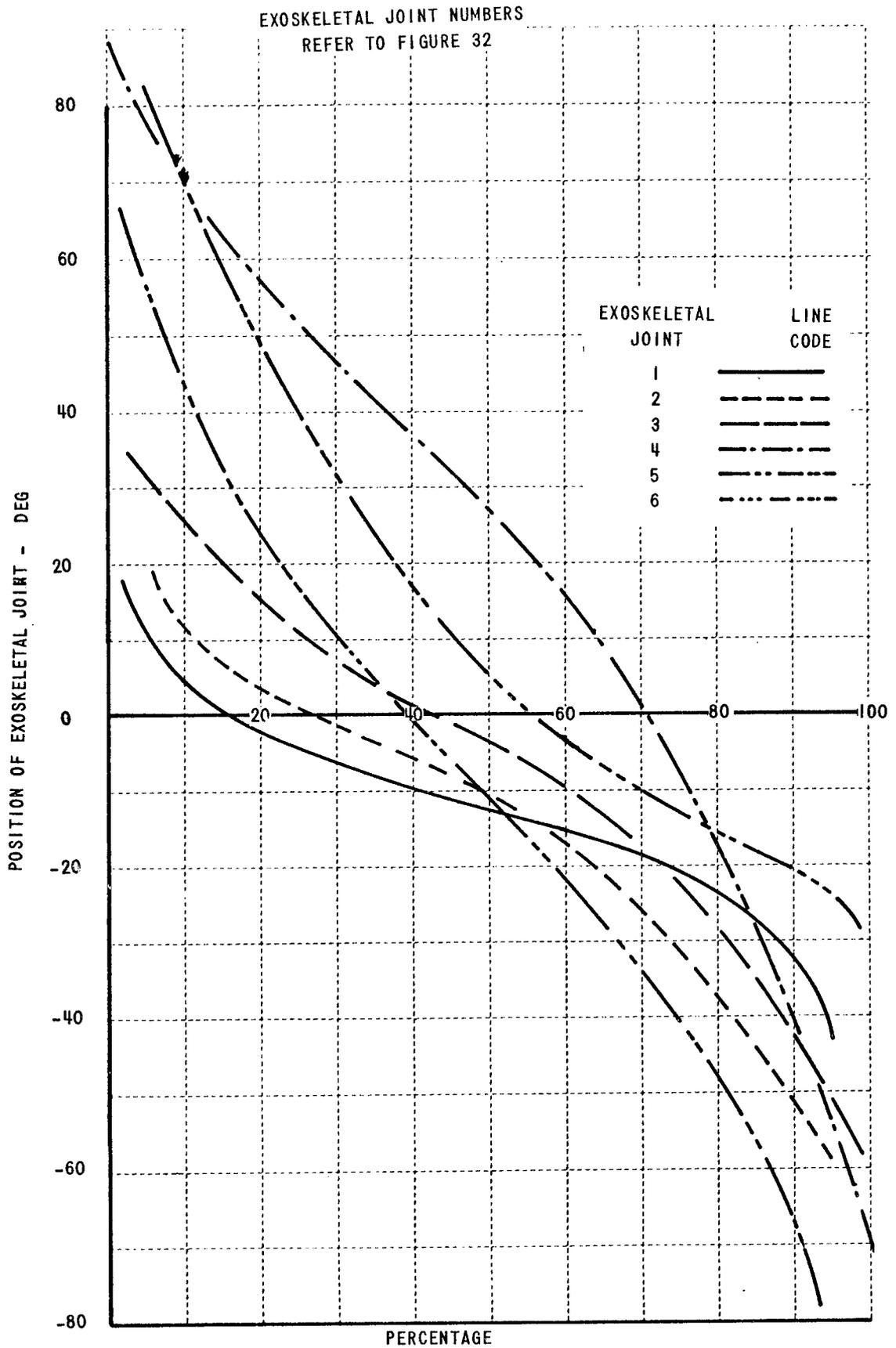
Figure 33
POSITION OF EXOSKELETAL JOINTS DURING TYPICAL SHOULDER AND ARM MOVEMENTS

The position of each exoskeletal joint was tabulated for each 0.1 second throughout the time of performance. Velocity and acceleration of the exoskeletal joints was computed by determining the change in displacement and in velocity during the known time increment. Figures 33, 34 and 35 present the percent of time that the position, velocity and acceleration of the upper-extremity exoskeletal joints exceeded particular values. The zero value of displacement is defined, for the above curves, as the position of the exoskeletal joints when the subject is standing erect, his arms at his sides.
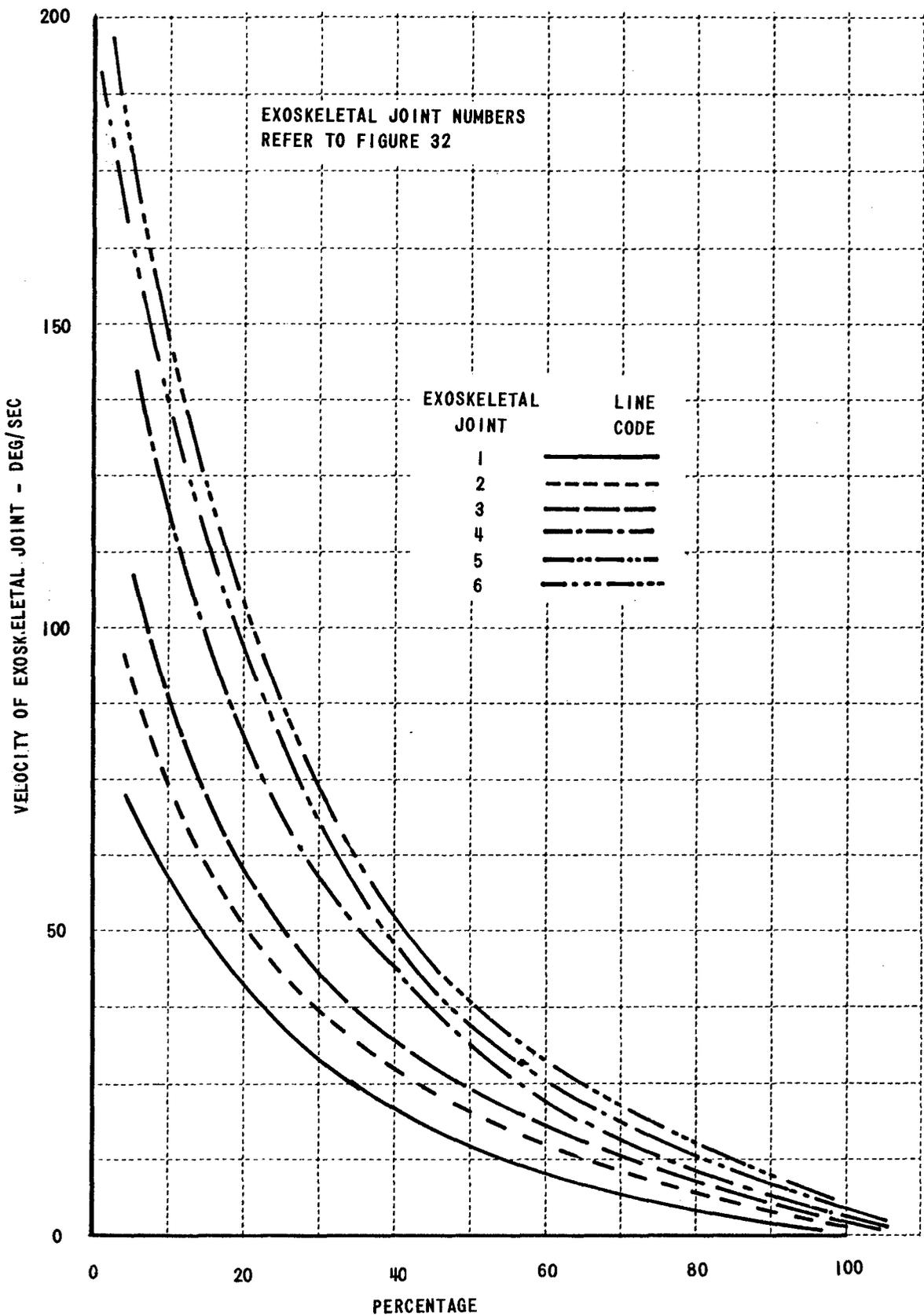
Figure 34
VELOCITY OF EXOSKELETAL JOINTS DURING TYPICAL SHOULDER AND ARM MOVEMENTS

VO-1692-V-3
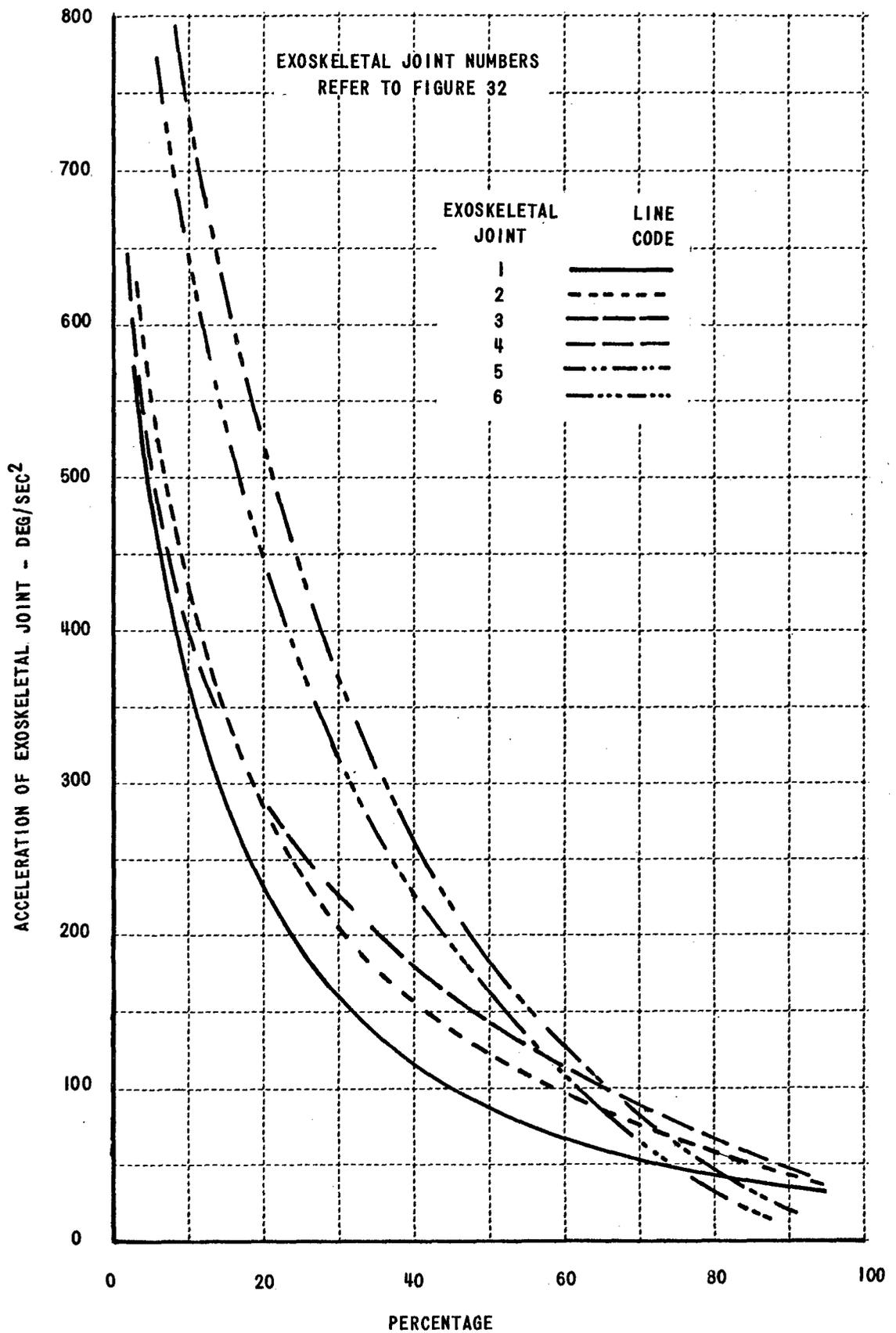
Figure 35

ACCELERATION OF EXOSKELETAL JOINTS DURING TYPICAL SHOULDER AND ARM MOVEMENTS

4. CONCLUSIONS

1. As noted earlier, one of the purposes of fabricating and testing a full-size, wearable, non-amplifying exoskeletal structure was to determine if it is feasible to surround a person by such a device. Conceivably, the device could either restrict normal body movements or, in some other manner, be so uncomfortable that the wearer would be unable to perform typical work tasks. However, results of tests offer evidence that, first, the motion restrictions caused by the exoskeleton are slight, and second, the performance of the subject is reduced only slightly by the restrictions. (The above comments refer to operation of the exoskeleton without restrictions to exoskeletal joint motion.) Consequently, it is concluded that it is feasible to surround a person with an exoskeletal device, as constructed during this program.

2. Throughout the tests conducted certain exoskeletal joints were not used. These joints were: (1) the exoskeletal joint that permits wrist flexion, (2) the exoskeletal joint that permits wrist ulnar and radial rotation, and (3) the exoskeletal joint that permits ankle abduction and adduction. During all tests conducted the subject either did not use the above motions, or he was able to perform equally well with the motion prevented. Consequently, it is concluded that future powered exoskeletal structures should not contain the above joints unless, due to a specific prospective application, it is necessary to do so.

3. The experimental data recorded represent typical tasks that would be performed with a powered exoskeletal device. Therefore, it is recommended that the data presented in this report in regard to motion ranges, velocities and accelerations at exoskeletal joints be used as design criteria for the powered Man Amplifier.

LIST OF REFERENCES

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2) Mizen, N. J., _Investigation Leading to the Design, Fabrication and Tests of a Full-Scale, Wearable Mockup of an Exoskeletal Structure_, Cornell Aeronautical Laboratory, Inc., Interim Technical Report VO-1692-V-1, October 1962.

3) Dempster, W. T., _Space Requirements of the Seated Operator_, WADC Technical Report 55-159, Wright Air Development Center, July 1955.

4) Dixon, W. J. and F. J. Massey, Jr., _Introduction to Statistical Analysis_, McGraw-Hill Book Company, New York, 1957.

5) Clark, D. C., N. J. DeLeys and C. W. Matheis, _Exploratory Investigation of the Man Amplifier Concept_, Cornell Aeronautical Laboratory, Inc., Report No. VO-1616-V-1, August 1962.