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PHASE TWO REPORT

HUMAN STRENGTH SIMULATIONS

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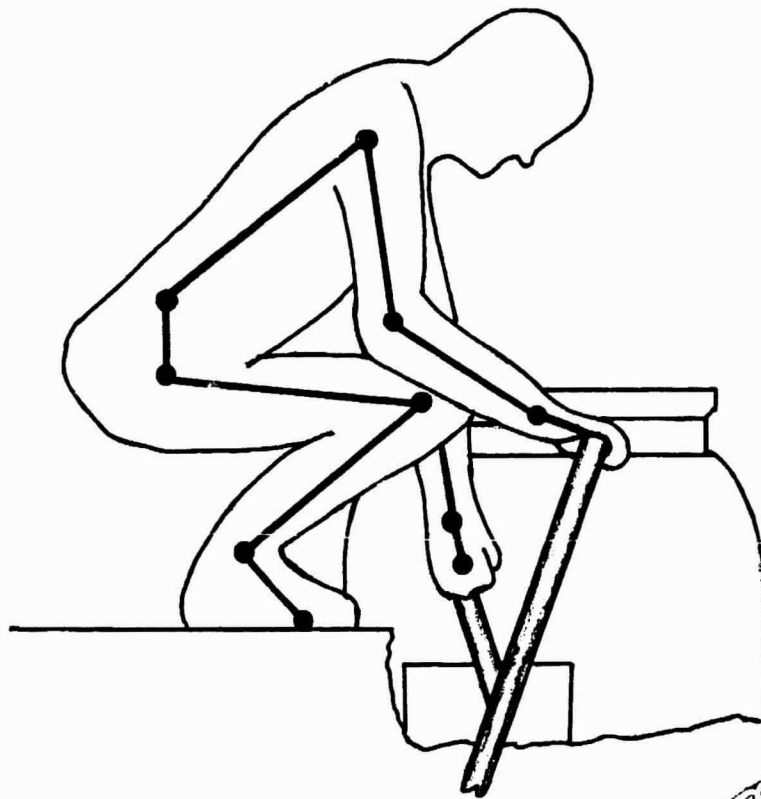
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THE UNIVERSITY OF MICHIGAN

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UNDER CONTRACT NAS9-10973 APRIL, 1972



PHASE TWO REPORT

HUMAN STRENGTH SIMULATIONS
FOR
ONE AND TWO-HANDED TASKS
IN
ZERO GRAVITY

by

Engineering Human Performance Laboratory

The University of Michigan

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for

National Aeronautics and Space Administration

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Don B. Chaffin, Ph.D.

Project Director and
Associate Professor of
Industrial and Operations
Engineering

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Human Strength Simulations For One
and Two Handed Tasks in Zero Gravity

I. Introduction

It is the purpose of this document to extend the strength simulation results presented in the Phase One Report to consider the following specific conditions:

1. One hand is active in the task.
2. Both hands are active, but with different force directions on each, (e.g., the right hand is pushing-out while the left hand pulls-in).
3. Zero gravity conditions exist, with body bracing provided by either, 1) the portable foot restraint assemblies (lock-on shoes) when standing, or 2) a lap-belt when seated.
4. Shirt-sleeved individuals.
5. Male population strengths with anthropometry matching to the astronauts.
6. Static or slow movement tasks with a maximum length of four seconds and a minimum rest of five minutes between exertions to minimize muscle fatigue.

7. A wide range of hand positions relative to either the feet or to the bisection of a line connecting the hip centers, with normal range-of-motions at each body joint.

The strength simulations performed for these conditions are possible due to the development of both a Three - Dimensional Hand Force Capability Model for the Seated Operator¹ and A Biomechanical Model for Analysis of Symmetric Sagittal Plane Activities². Brief descriptions of these models will be presented later in this report. What these models provide when combined is the capability to predict the hand forces that could be expected of an anthropometrically defined proportion of the population when performing under the conditions prescribed in the preceeding. By implementing these models on a digital computer it has been possible to select specific conditions for strength simulations of interest to NASA/MSC personnel, as well as to predict strength variability for a broader set of general workplace dimensions and personnel anthropometry.

Specifically, two types of strength simulations were completed. The first had to do with potential strength tasks

¹This is a Ph.D. dissertation performed by Mr. Frederick Schanne as part of the project. It is available through University Microfilms, Inc., Ann Arbor, Michigan.

²This is the earlier strength modelling efforts by Chaffin and Baker, as reported in AIIE Transactions, Vol. 2 (1), 1970, and more recently by Martin and Chaffin, as reported in AIIE Transactions, Vol. 4(1), 1972.

aboard Skylab. The objective of the simulations was to demonstrate the effects of various body configurations, hand positions, and human anthropometry on human strengths in several selected operational tasks. The tasks were chosen to have potentially large force requirements due to either the manipulation of a mass or pulling against a mechanical linkage. The tasks simulated were:

1. Raising and alligning ASMU in position between paddle restraints in M509 experiment.
2. Rotating ASMU into service position in M509 experiment.
3. Removing PSS from PSS storage rack in M509 experiment.
4. Installing PSS in ASMU in M509 experiment.
5. Positioning food container above freezers.
6. Operating control levers on trash ejector.

The second set of strength simulations was meant to assist in the general design of future workplaces. Here the objective was to present in tabular form one-handed force predictions for various control placements and directional movements for the seated operator in zero gravity. The hand positions were chosen to be at three heights above the hips and at coordinates of a 4 x 8 inch grid ranging from eight inches to the left of center, to 36 inches in front of the operator, to 32 inches to the right of the operator.

The order of reporting these developments is as follows:

Section II -- Description of Biomechanical Strength
Model and Input Data

Section III - Results from Simulations of Specific
Skylab Tasks

Section IV - Predicted Hand Forces for Seated Operator

Section V - Summary

II. Description of Biomechanical Strength Model and Input Data

The Phase One Report described the development of the Sagittal Plane Biomechanical Model used for the two-handed strength simulations which comprised the bulk of that report.¹ Though conceptually similar, three-dimensional strength simulations are different enough to warrant further description here.

Essentially the three-dimensional strength model was developed by merging the three-dimensional biomechanical model for the seated operator developed by Schanne, 1972, with the earlier two-dimensional strength model. In doing this it was assumed that the legs would act in the sagittal plane during the exertions, and thus the existing two-dimensional model of the leg strengths was sufficient. In other words, the three-dimensional model of Schanne's was used to evaluate the strengths of the torso, shoulders, and arms, while the leg strengths were evaluated by the two-dimensional model.

At first this two-dimensional leg strength assumption may sound restrictive, since in general external forces can act to rotate the body in a side-to-side direction, (i.e., in the frontal rather than sagittal plane). However, since in this project the astronaut when exerting a force in the

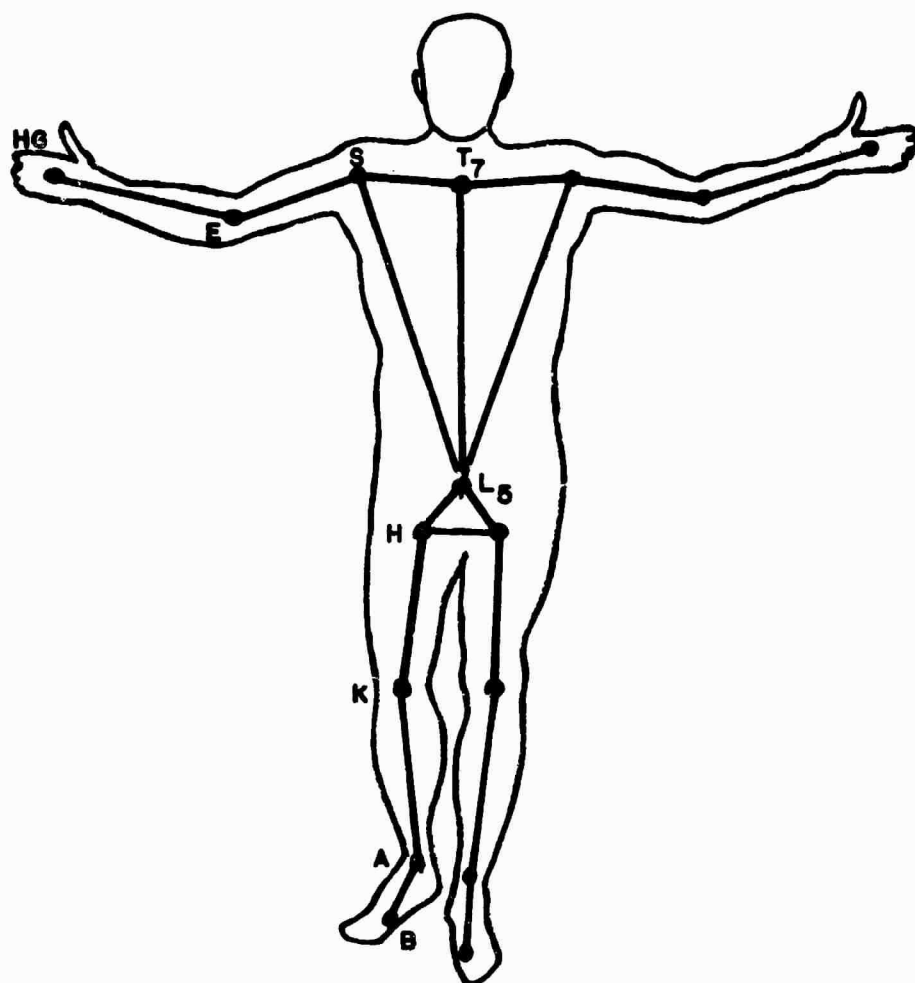
¹The reader is also referred to Chaffin and Baker, 1970, and Martin and Chaffin (1972) for further descriptions of this type of model

standing configuration is assumed to have his feet secured by the portable foot restraint assemblies, the side-to-side acting forces, which would normally throw a person off-balance can now be overcome by the leg strengths without having to place the feet far apart and thus out of the sagittal plane. Hence the assumption that the leg forces and torques will act primarily in the sagittal plane. Hence the assumption that the leg forces and torques will act primarily in the sagittal plane during exertions in zero gravity is believed to be warranted. It should also be noted that any side-to-side muscle strength limitation will be evaluated specifically as a lateral bending strength component of the torso, as described later. Thus side acting forces are not neglected entirely, but their effect on how much force a person can resist or volitionally create in a maximum exertion is determined at the torso rather than the legs.

Strength Model Assumptions

The following are the assumptions used to develop the human strength model. As mentioned previously, many of these same assumptions have been used by other biomechanics researchers, (e.g., Dempster, 1955, Plagenhoef, 1966, Pearson, et al., 1961, Fisher, 1967, Williams and Lissner, 1962, and Hanavan, 1964.)

1. The person can be represented by a system of 12 links and three plans, as depicted in Figure 1.



Notation:

HG - Center of grip of the hand
 E - Elbow joint centers
 S - Shoulder joint centers
 T7 - T7/T8 vertebral disc center

L5 - L5/S1 vertebral disc center
 H - Hip joint centers
 K - Knee joint centers
 A - Ankle joint centers
 B - Ball of foot

FIGURE 1

LINKAGE REPRESENTATION

These links are similar to those used by Kilpatrick, 1971, and Schanne, 1972, for the torso and arms, and Chaffin and Baker, 1970, and Fisher, 1967, for the legs.

2. The forces applied by the person act at the center of grip of the hands, and the grip strength is adequate in all exertions. This assumption is justified on the grounds that for those tasks where potential hand forces are to be encountered a gripping area (e.g., fingers can wrap around object) is usually provided for the hands. It has been reported that with a reasonable gripping areas, higher forces (generally above 100 pounds, from Schmidt and Toews, 1970) can be generated by the hands than are generated by the rest of the musculature. Specific grip strength values could be added later to the model if deemed appropriate for situations where a full hand grip is not possible.
3. Because the model is to be used in zero G, and for tasks where only static or slow movements are to be encountered, mass distribution throughout the body links is not important. It might be noted that a version of the model has been developed for one G applications which does contain assumptions regarding mass distributions.

4. The body balance is not lost in that either the person is seated with a lap-belt that tightly secures the pelvis, or is standing with his feet locked in the portable foot restraining assemblies (lock-on shoes).
5. All analyses are static in nature, thus isometric strength data are applicable. This is the state-of-the-art in as much as, (a) dynamic muscle strengths are not well quantified, (b) acceleration components during dynamic activities are difficult to quantify, and (c) the force capability output from such models is complex and thus cannot be easily applied to general activities (see Chaffin, et al., 1967). It should be mentioned that in most high force exertions slow well-controlled actions are present, thus isometric models are directly applicable.
6. The strength of the left arm is assumed to be a fixed 91% of the right arm. This is based on many investigator's data, as summarized by Schanne, 1972.
7. The maximum hand force predicted by the model for any given body position is a function of the isometric strength of specific muscle groups. This assumption allows the strength data gathered by both these and other researchers to be used as

input to the model. (The data will be described later in this section). Thus muscle strength is the only limiting factor in the model.

8. A specific muscle strength limitation is a function of the angles of the joints spanned by the muscles involved. This assumption has been applied successfully in the simple two-dimensional model reported in the Phase One Report. The strength-angle relationships for the legs are reported in the Phase One Report, and for the torso and arms by Schanne, 1972.
9. The maximum predicted hand force is the force which when applied to the hands produces a resultant torque at one of the linkage articulations of a magnitude that is equal to or less than the reactive muscle torque that can be volitionally created in an isometric exertion at the same articulation. Thus, hand force capabilities are based on comparison of muscle torques and resultant torque at each articulation. This has been substantiated by the earlier work reported in the Phase One Report, as well as by the empirical investigations of Schanne, 1972, and Ramsey and Purswell, 1971. A further discussion of this logic is presented later in this Section.

10. Wrist strengths are not considered an active limit in whole-body exertions. This is based on the fact that the validation studies by Schanne, 1972, performed on the three-dimensional model disclosed that the model without wrist strengths generally under-predicted whole-body strengths, and thus the addition of another active strength limit, which further complicates the model, was not warranted.
11. The correction technique developed by Schanne, 1972, for changing the consistent underpredicting aspect of the three-dimensional model was retained until research can be completed to more fully understand how the multijoint muscles act as functional groups to increase the whole-body strengths. Without this bias correction factor the three-dimensional model hand force predictions correlated in past studies to actual hand forces with $r=.75$. The correction factor raised this to $r=.83$, which is equal to the value for the two-dimensional model used in the earlier Phase One effort.

Model Input Data

To complete the hand force simulations described in Sections III and IV various input data were needed. In

general these are of the following two types (the specific formats used for the input values are described in Appendix A):

1. Subject characteristics, and specifically:
 - A. Body segment lengths
 - B. Strengths of specific muscle actions
(e.g., elbow flexion, knee extension,
inward humeral rotation, etc.).
2. Task requirements, and specifically:
 - A. Body configurations
 - B. Hand force directions
 - C. One hand or two hand task

The subject data segment lengths were developed from the proportional scaling technique used by Dempster and Graughran, 1967. Essentially this required each dimension to be a given fraction of the stature. The astronaut stature distribution was used. Table I summarizes the results of this procedure. When these dimensions were compared against similar dimensions obtained on 50 males of the same age distribution as the astronauts less than a 2% error in the means was produced. Thus it is assumed that the stature provides a good estimate of the needed size dimensions.

The subject muscle strengths were estimated from muscle strength data of these and other researchers. The leg and arm strengths were based on the earlier studies of these

TABLE I
Input Anthropometric Size Data

Dimensions*	Units	Source	Proportion of Males Larger than:		
			95% (small)	50% (average)	5% (large)
Weight (nude)	pounds	1	142.9	167.2	191.5
Stature (std. relaxed)	inches	1	67.0	70.0	73.0
Lower Arm Length	inches	2	9.5	10.2	10.9
Wrist-to-grip Center	inches	2	3.3	3.8	4.3
Lower Leg Length	inches	2	15.2	16.5	17.9
Foot Length	inches	1	8.2	10.0	11.8
Std. Elbow Height	inches	2	41.9	44.5	47.3
Hip-to-Hip Width	inches	2	7.5	9.3	11.1
Shoulder-to- Shoulder	inches	2	12.7	14.4	16.1

*Definitions conform to definitions stated by Dempster (1955).

Reference Source:

1. Distributions were developed from unpublished astronaut anthropometry, with assistance of NASA-MSC, Behavioral Performance Group.
2. Distributions were estimated based on astronaut statures using the technique proposed by Dempster and Gaughran, 1967. A comparison of these values with the 50 males selected for the strength measurements showed less than a mean 2.0% error with the stature-based estimates.

investigators (see Chaffin and Baker, 1970), which have since been augmented to include 50 males.

Where the additional three-dimensional strengths were needed (e.g., in the torso, arm rotation, and shoulder strengths) Schanne's three-dimensional data gathered on ten young men were used. To assure consistency between the samples, Schanne's smaller data base was compared to the most nearly similar strengths in the Chaffin and Baker data. Specifically, this required that the mean muscle strengths of the two samples, (obtained using the same positions and muscle actions) were used to form a correction factor. This then was applied to the Schanne data to raise or lower these strength values so that they were similar to the larger Chaffin and Baker sample data. Table II summarizes the resulting values.

The task data used as input in the model simply relates to the configurations of the body that might be of interest to the designer, and to how forces act on the body during a task. The body configurations are specified as angles of the joints through which the model will iterate in prescribed increments. As an example, the lower leg might be specified as being sequentially placed in positions of 70°, 80°, 90°, and 100° from the horizontal reference axis. (Appendix A describes the format designations for these data.)

In addition to specifying the body configuration angles, it is necessary to input the hand force directions and

TABLE II

Input Strength Data (inch-pounds)

Sagittal Plane Muscle Actions**	Source	Proportion of Population Stronger than:		
		95%	50%	5%
Elbow Flexion	Chaffin & Baker***	436	616	821
Elbow Extension	Singh et al., 1966	282	380	491
Shoulder Flexion	Chaffin & Baker	518	744	1001
Shoulder Extension	Chaffin & Baker	521	738	986
Hip Flexion	Elkins, 1951	1029	1359	1734
Hip Extension	Chaffin & Baker	1653	2989	4513
Knee Flexion	Clark, 1966	355	456	571
Knee Extension	Chaffin & Baker	1020	1614	2293
Plantar Flexion	Chaffin & Baker	1118	1970	2941

**These data were used in estimating other non-sagittal plane strengths based on Schanne's data (1972), as described in Appendix C. The result is the set of strength coefficients necessary as input, as described in Appendix A.

***The major muscle strengths were obtained in a manner described by Chaffin and Baker (1970) with the cooperation of 50 male employees of the Western Electric Company, Kansas City Works. These employees matched-out to be one inch shorter than the astronauts, but of the same average weight.

whether the person is seated or standing. In the former it is assumed that the pelvis is solidly fixed (either in a seat with the lap-belt secured or the person has placed his pelvis and legs against some object which secures them). If he is standing, it is assumed that he has secured his feet at the balls-of-the feet by either the portable foot restraint assemblies or by wedging them tightly into the floor grid.

Strength Model Methodology

The model is capable of performing two basic types of analyses:

1. Given a specific body configuration and force direction operating on the hands, it will predict the maximum hand force capability for one or two-handed activities.
2. Given the force direction operating on the hands and the hand positions, it will determine the body configuration which yields the maximal hand force capability, i.e., it will find the body configuration in which the person is the strongest for the given force direction operating on the hands.

This latter simulation model was used for the strength simulations employed in this study. In this analysis the legs and torso positions are discretely varied, as determined by the input data. For each torso and leg position, 25 different arm positions are determined by the following

criteria: (1) the arm configurations vary discretely throughout the voluntary ranges-of-mobility of the shoulder and elbow, and (2) if the straight-line distances between the shoulder and the specified hand locations is smaller than the length of the arm (i.e., a feasible arm reach distance exists), then the arm is always configured with its proximal end-point being at the shoulder coordinates and its distal end-point being at the specified hand coordinates. (Appendix B contains a description of this algorithm.) This then provides the capability for the design to simply specify the hand coordinates (which are usually needed due to hardware constraints, such as hand hold locations, size of object, etc.) and a set of leg and torso configurations of interest. The model then positions the arm so it connects the shoulder and hand coordinates during each different body configuration simulated.¹

Once a specific body position has been determined, the hand force magnitudes are iterated in a binary search for the largest value that can be developed by the various muscle actions. As was stated under the model assumptions, this is accomplished by comparing the torques produced by the muscle groups which act at each articulation in the linkage representation (see Figure 1 on page), with the torques produced by the assumed hand forces. For reference, the muscle produced torques are referred to as reactive

¹The model also can be used by specifying the arm configurations as input, and letting the hand coordinates vary.

torques, and the hand force produced torques are resultant torques. In other words, the muscles react to the torque resulting from the forces acting on the hands.

The value of the reactive muscle torques is computed as a function of both the input isometric strengths and the angles of the body links. The relationships of body angles and strengths for the torso and arms have been empirically developed by Schanne, 1972. Similar relationships for the legs have been reported in the Phase One Report for this project. The use of these strength/angle relationships provides the means to modify the input strength data obtained in specific positions to the other positions assumed in the various simulations.¹

Once the various muscle reactive torques have been computed for a specific body position, the hand forces are iterated until at least one of the articulation resultant torques is increased to a level where it is equal to the same articulation's muscle reactive torque. Thus the maximum hand force is achieved for that position when one of the resultant torques at a joint is equal to the muscle reactive torques at the joint, and all other joint resultant torques are smaller than the muscle reactive torques.

The maximum hand forces are then stored, another body position is selected, and the torque comparison once again

¹The technique is also described in the Martin and Chaffin paper, 1972.

is completed. When all specified positions of the body have been simulated, the list of corresponding hand forces is searched for the largest values. These and the associated body configurations are then outputted in both body angles and in a graphical form. (Appendix B contains a typical output).

The preceding methodology is presented in Figure 2 as a logic flow diagram. (Appendix B contains important detailed logic statements).

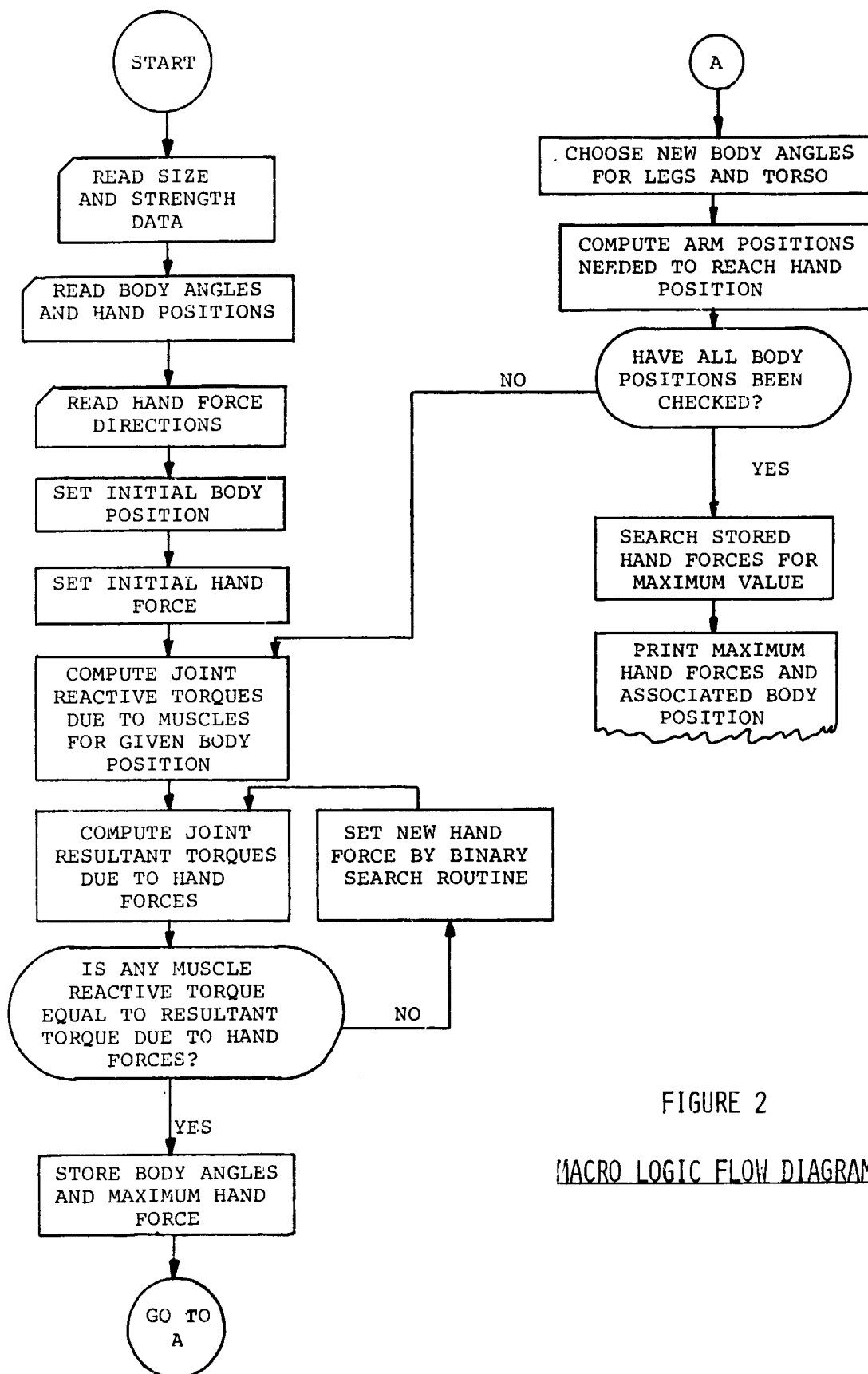


FIGURE 2

MACRO LOGIC FLOW DIAGRAM

III. RESULTS FROM SIMULATIONS OF SELECTED SKYLAB OPERATIONS

This section presents the results obtained from applying the human strength simulation model described in the preceding section to preselected tasks to be performed aboard the Skylab. The task selection was based on the following considerations:

1. A potential strength problem could exist due to:
 - A. Large masses being manipulated.
 - B. Awkward body positions.
2. Documentation (drawings and procedures) and training support personnel were available to provide the necessary dimensional input data.
3. Varied types of strength outputs were required (i.e., one hand, two hands, lifting, pushing, push/pull, etc.).

Evaluation of the various tasks by these criteria was completed in consultations with Dr. William Feddersen, the Project Technical Monitor, Mr. Robert L. Bond, Special Assistant to the Chief of the MSC Spacecraft Design Office, and Mr. Robert McBrayer, MSFC Human Factors Engineering Section. The evaluation resulted in the following activities being selected:

1. Raising and aligning ASMU in position between paddle restraints in M509 experiment.

2. Rotating ASMU into service position in M509 experiment.
3. Removing PSS from PSS storage rack in M509 experiment.
4. Installing PSS in ASMU in M509 experiment.
5. Positioning food container above freezers.
6. Operating control levels on trash ejector.

The input data necessary to describe these activities were gained from the following sources:

1. "Skylab Design Requirements Drawings", number 1B77075, prepared by Douglas Aircraft Company, Inc., revised November 10, 1971.
2. "Skylab Experiment Operations Handbook", number MSC-00924, prepared by MSC Crew Procedures Division, revised June 7, 1971.
3. Various photographs, dimensions, and movies obtained from visits to the Skylab Mockup.
4. Demonstrations of procedures in the Skylab Mockup by both Mr. Robert McBrayer of the MSFC Human Factors Engineering Section and Mr. Louis V. Ramon, of the MSC Flight Missions Operations Section.

As mentioned earlier, the type of task input data required is primarily dimensional in nature. Specifically, what was gathered is as follows:

1. The varied positions of both hands relative to the center of the portable foot restraint assembly on the right foot during the exertions of interest.
2. The direction of the forces acting on each hand during the exertions of interest.
3. The feasible body positions that should be included in the simulations.

These data along with specific simulation objectives were established for each activity. The following describes the simulations of each activity. What is presented in each case is a discussion of the simulation objective, the input data, a graphical presentation of the results, and a discussion of the results.

Raising and Aligning ASMU in Position Between Paddle Restraints

This activity was chosen for simulation due to the relatively large ASMU mass (approximately 180 pounds in one G weight equivalent), which has to be raised vertically from the launch position to a storage position. The previous strength simulations of two handed lifting have shown that the hand force capability is more limited when the hands are near the waist/chest height than when either above the shoulders or below the hips. This is due to the use of the limited arm strengths when at the

waist/chest height as opposed to using the stronger back and legs at other heights.¹ It was also disclosed by the earlier strength simulations that the lifting strengths at the waist/chest height were greatly dependent upon how close the object was (in a horizontal direction) to the torso.

Based upon both of these considerations it was decided to simulate the lifting activity with the ASMU at the height needed to make the final aligning actions before securing in the paddle restraints. This height is at the more limited waist/chest height. A configuration for the hand positions was adopted that had the left hand at the bottom of the ASMU and the right hand at the top. This would allow the producing of the rotation type motions needed for the final alignment, as discussed in the next subsection.

Four horizontal foot placements were studied (5, 10, 15, and 20 inches) with the hope that this could provide some training assistance by disclosing the distance that would provide the highest hand force capability. Such a recommendation could provide time savings, since "trying out" varying foot placements with the portable foot restraint assemblies is time consuming. The left foot was assumed to be 12 inches behind the right foot in each simulation.

¹See Phase One Report - Graphical Predictions of Human Strengths, NAS9-10973, Biomedical Division, NASA/MSD, April, 1971, pp. 65-66.

The average (50%) anthropometric characteristics were used to demonstrate the above effects. A set of 1500 body configurations (varying from the erect leaning back and forwards to a slight squat) were attempted for each foot placement.

Results of Simulating ASMU Raising. The maximum predicted hand force (in pounds) and the body configurations recommend to achieve the forces are displayed in Figure 3. The limiting strengths are due to the shoulders. When in close (Positions A & B) the right arm needs to be positioned out of the sagittal plane (the shoulder is abducted), and this limits the lifting strength to slightly below that achieved when at 15 inches. The 15 inch distance (Position C) also allows for a greater selection of body positions. The 20 inch distance (Position D) displays the significant decrease in lifting strengths that occurs with relatively large horizontal distances. In fact, from 15 inches and larger the right hand lifting force decreases at this height due primarily to a shoulder strength limitation. (Section IV discusses these general findings in more detail). Thus it is recommended that the center of the portable foot restraining assembly (ball-of-foot) on the right foot be placed between 10 and 15 inches from the front of the ASMU when lifting it into the paddles, as illustrated in Positions B and C.

It also should be noted that based on the 50% man's

Simulation Objectives - To demonstrate the effects of four different foot placements on the hand forces necessary to lift the ASMU prior to securing in paddle restraints (reference is Procedure 09.005.001-0 (M509) Step 30 in Skylab Experiment Operations Handbook).

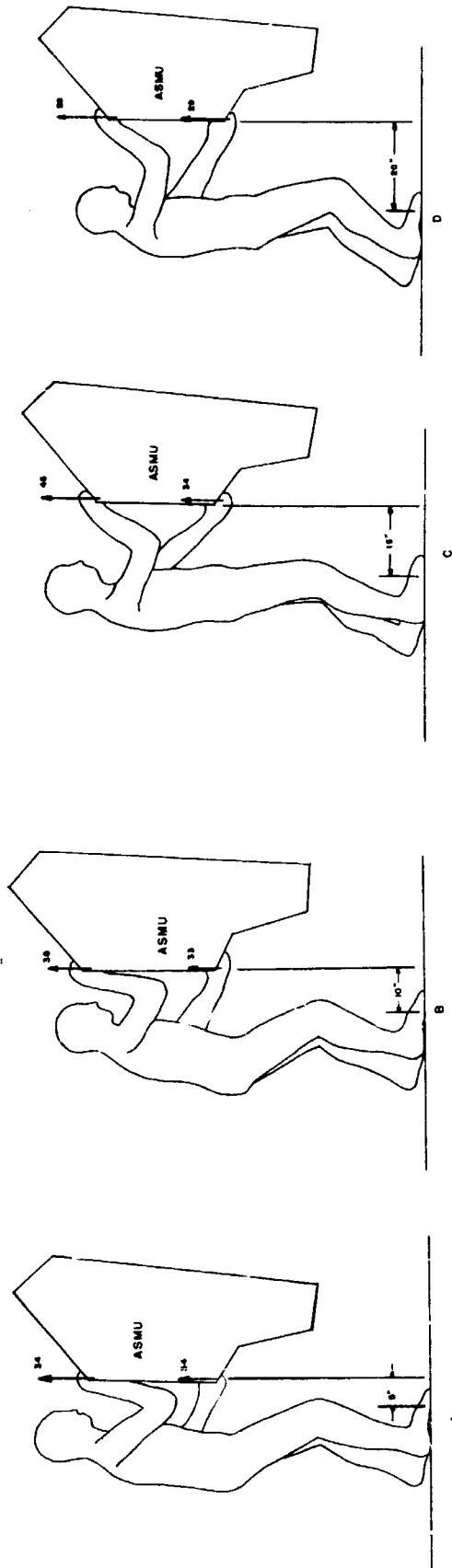


Figure 3 Raising and Aligning ASMU in Position Between Paddle Restraints

predicted lifting forces the lifting of the ASMU should be accomplished with low velocity profiles, since only approximately 1/3 of the weight can be lifted with both hands. If for instance the ASMU were caused to move downwards (due to some prior force acting on it) with an average linear velocity of one foot-per-second, and the maximum hand forces were steadily applied to stop its motion, its downward momentum would still carry it over 1/2 inch during the period of the maximum hand force application. Thus it can be seen that even with this low initial movement velocity, the stopping distance may not be acceptable unless the hand forces are applied at precisely the correct moment to stop the motion in an allowable distance. Though this example is oversimplified, it serves to illustrate that low-velocity profiles (probably less than 1.0 fps) are needed in large mass handling. Though high hand forces can often be produced while the body is in one position, and thus a large velocity imparted to an object, the ability to quickly and accurately stop its motion may not be as easily achieved due to a more awkward body position being necessary near the termination of its trajectory.

Rotating ASMU to Service Position

In evaluating the manipulation of the ASMU, a question arose as to the amount of torque that normally could be created when attempting to rotate the ASMU into the

servicing position. In this case the ASMU is not freely moving, but is secured between the paddle restraints which only allow rotation.

From the available dimensional data and procedures the ASMU was assumed to be rotated following a procedure wherein hand forces are applied as illustrated in Figure 4. Once again, the question of foot placement was evaluated in a manner similar to that used in the preceding ASMU lifting simulation. The average (50%) male anthropometry was assumed, with about 1500 different body configurations being tried for each foot placement.

Results of Simulating ASMU Rotation. The maximum rotational torque about the assumed axis of rotation was used as a measure of effectiveness. Figure 4 presents the predicted hand forces and rotational capabilities, as well as the associated body positions that are most effective in producing the predicted hand forces.

In general, when in close to the ASMU the limited shoulder strengths cause the model to predict a more "crouched" configuration (Positions A and B). When further away it is possible to stand more erect and "lean back" (as far as the left arm will permit) to achieve the maximum hand forces (Positions C and D). The rotational torque capability is not predicted to decrease significantly until the person stands at a distance greater than 20 inches.¹

¹The slight decrease in torque capability in Position C is not deemed significant.

Simulation Objective - To demonstrate the effects of four different foot placements on the hand forces necessary to rotate ASMU while secured in paddles (i.e. the left hand pushes against bottom of ASMU while right hand pulls on top of ASMU).
References is Procedure 09.005.017-0 (M509) Step 2 in Skylab Experiment Operations Handbook.

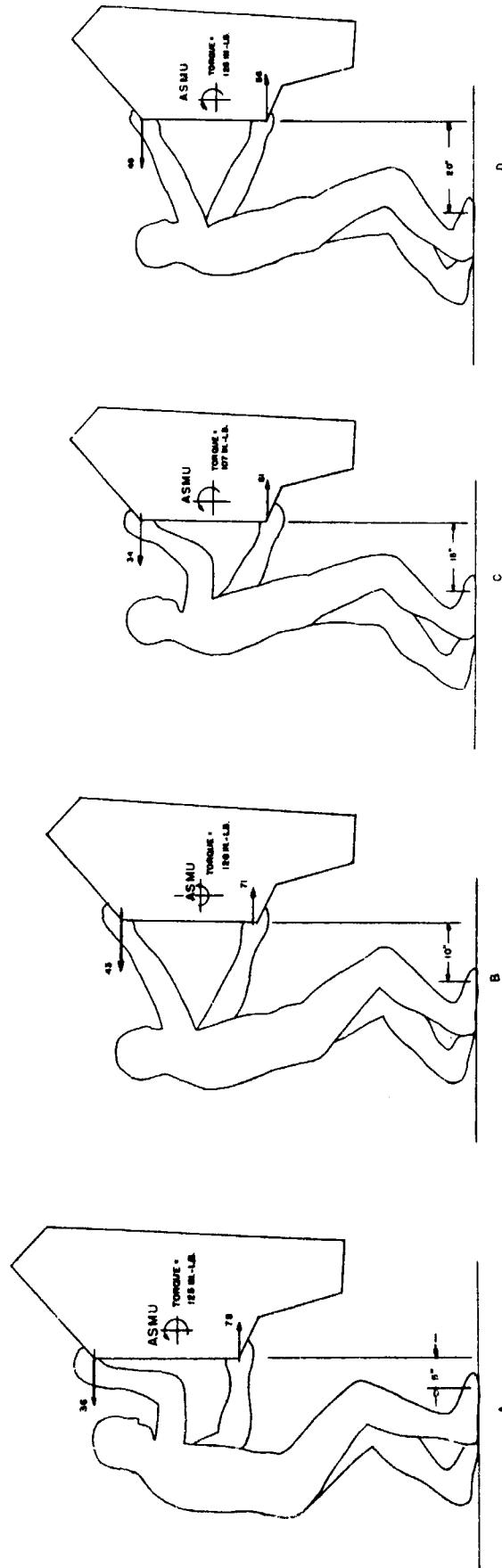


Figure 4 Rotate ASMU to Service Position

Removing PSS from PSS Storage Rack

When lifting a mass with one hand it becomes a question in both one G and in Zero G as to whether a leg or back lift allows a higher lifting force capability. This is especially true in lifting the PSS from its storage rack in that the rack will not allow the astronaut to straddle the PSS while lifting. (The straddling of any weight while lifting permits a higher force capability due to the better use of the leg and back muscles).

Figure 5 depicts the three back angles assumed, i.e., horizontal, 30° from the horizontal, and 60° from the horizontal. The average 50% male anthropometric characteristics were assumed. Also, 1400 body configurations were attempted, varying from a very deep crouch while leaning forwards to having the legs almost straight while leaning backwards.

Results of Simulating the Removal of the PSS from Storage Rack. The right hand lifting capability was used as the measure of effectiveness. In other words, the left hand simply acts as a stabilizer in case of any motion perpendicular to the vertical. Figure 5 describes the results. These clearly indicate that the 30° torso orientation with a slight lean forward over the PSS (Position B) will provide maximum hand force capability and thus control. The horizontal torso (Position A) causes the right elbow to be highly loaded, while the more erect 60° torso (Position C)

Simulation Objective - To demonstrate the effects of various torso orientations on the one-handed lifting capability when removing PSS from PSS Storage Rack (ref. procedure 09.005.010-0 (M509) Step 5 in Skylab Experiment Operations Handbook).

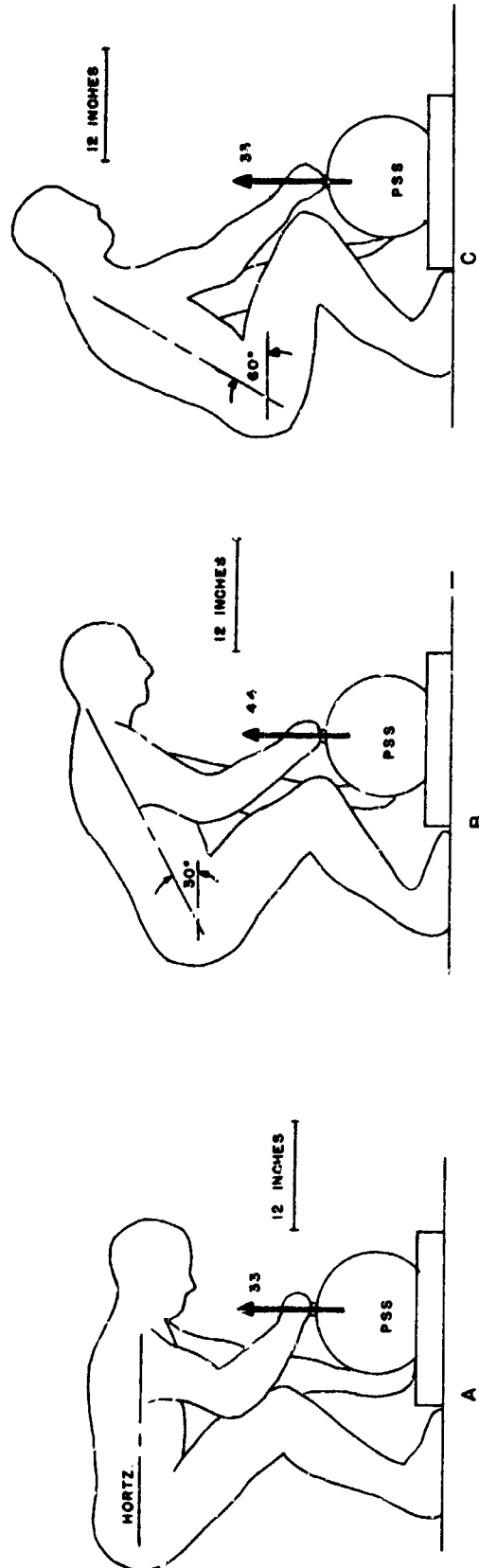


Figure 5 Removing PSS from PSS Storage Rack

causes the back and right shoulder to be the limiting factor.

Since the one G weight of the PSS is about 55 pounds, the 44 pound lifting capability in Position B should provide enough force for good motion control.

Installing PSS in ASMU

The installation of the PSS into the ASMU requires both lifting and pulling type forces to be exerted. Good alignment is necessary, thus the higher the force capabilities the easier the alignment.

A question as to how to position the hands to allow the highest hand forces was evaluated by simulation. Figure 6 depicts the various hand forces and force directions. Average (50%) male anthropometric characteristics were used. Also 2700 body configurations (varying from a semi-crouched to an erect and leaning back) were attempted for each task. The left foot was assumed to be placed 12 inches behind the right.

Results of Simulating PSS Installation in ASMU.

The vertical hand force predictions are depicted in Positions A and B. Position A allows lifting forces to be applied, but because the handle held in the right hand is aligned in a horizontal plane a downward force vector could not be developed by either hand if needed. Position B assumes a two-handed "basketball" grasp which provides both upward and downward forces to be applied.

Simulation Objective - To demonstrate effects of hand positions on hand forces necessary to install PSS in ASMU (ref.Procedures 09.005.019-0 (M509) Step 5, in Skylab Experiments Operations Handbook).

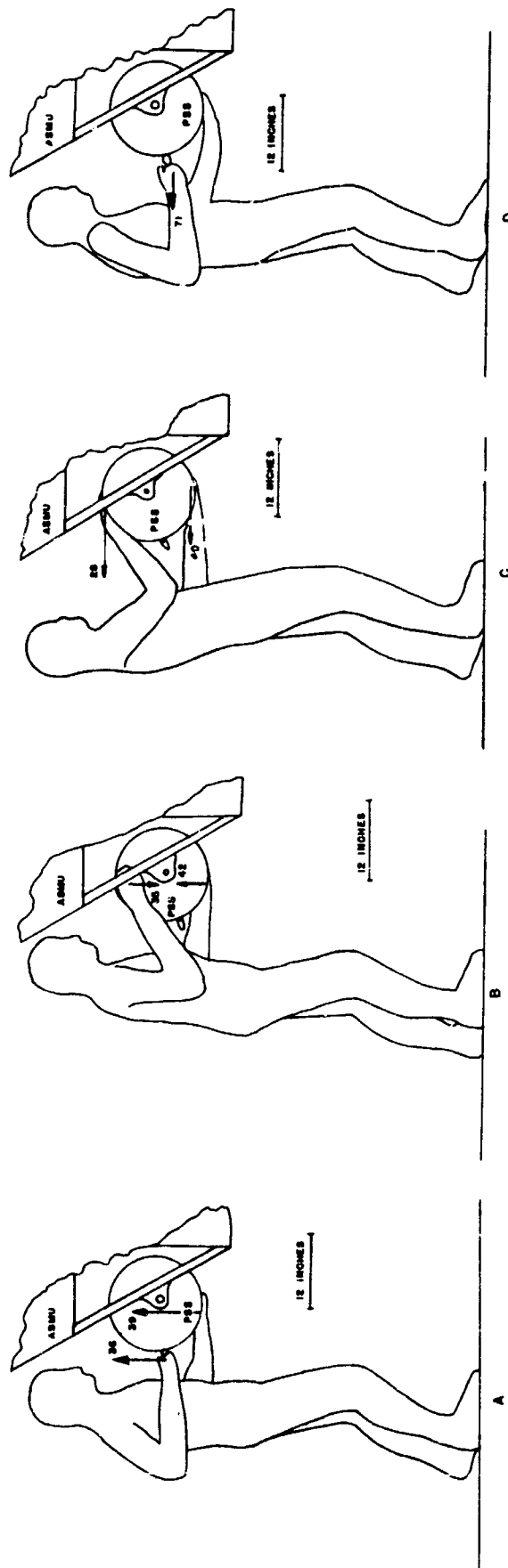


Figure 6 Installing PSS in ASMU

Position C shows that a similar grasp as in Position B also allows an effective pulling force to be developed, if a lean back body configuration is assumed. Position D gives a similar pulling force prediction using the handle.

In general, the hand forces predicted in Positions B and C should be quite adequate for aligning the 55 pound PSS in the ASMU, and these also provide force capability in directions other than those simulated.

Positioning Food Container Above Freezers

The largest masses to be manually transported on Skylab are the food containers (257 pounds loaded weight). One of these (number F550 on Skylab Design Requirements Drawing, number 1B77075) must be installed above the storage freezers for the orbiting configuration. This means that the final positioning of this large mass will be done with the astronaut in a position with his hands over his head, as depicted in Figure 7. At present there appears to be no other obvious foot restraints than on the floor.

The evaluation of how much force could be developed when in this position was done assuming three hand force directions, one with both hands lifting, one with both hands pushing, and one with the right hand pulling and the left hand pushing. This latter simulation depicts

Simulation Objective - To demonstrate the effects of various force directions on hand force capabilities in the extreme reach element required in positioning the food container (no.F550) above the storage freezers for orbiting configuration.

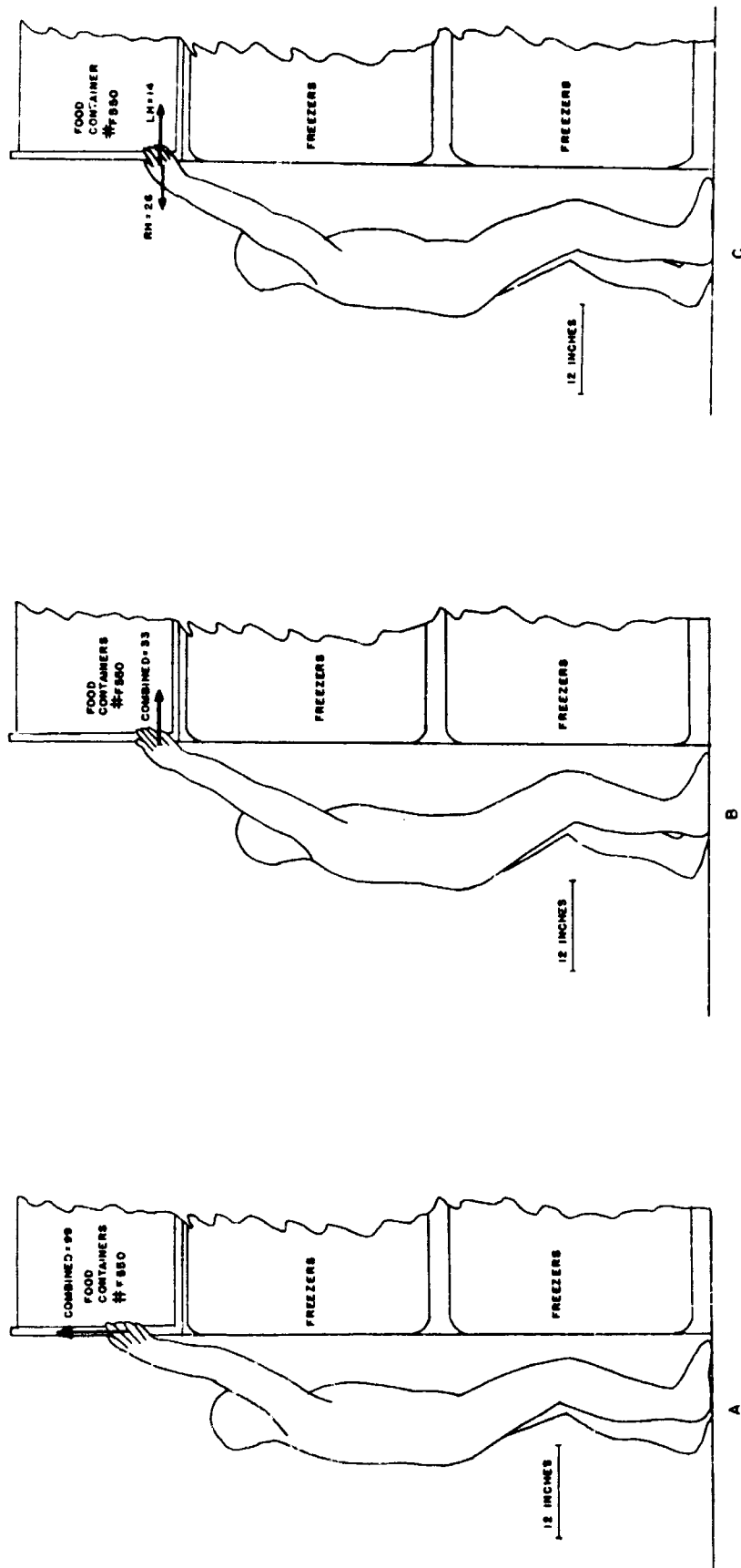


Figure 7 Positioning Food Container F550 Above Freezers

an attempt to rotate the container about its mass center-of-gravity.

Both average 50% male and large/strong 5% male anthropometric characteristics were used. Though 800 body positions were attempted, only about 20% of these were feasible due to the necessary extreme reach. The left foot was assumed to be 12 inches behind the right.

Results of Food Container Positioning Simulations.

The predicted hand force capabilities are depicted in Figure 7 for the average male and in Figure 8 for the large/strong male. In general, the lifting forces may be adequate provided extremely low velocity profiles are used, as discussed earlier regarding the ASMU lifting task. What is especially alarming, however, is the relatively low pushing forces (Position B) and rotational type forces (Position C). These forces are between about $1/4$ and $1/8$ of the weight of the container. Thus, to stop the container when moving with an initial average velocity of one foot per second could take approximately $1-1/2$ inches of additional motion using a maximum exertion. If the container was moving with a higher average velocity of two feet per second the stopping distance would increase to about six inches.

It is also worth noting that a simulation was attempted using the small (95%) male dimensions, and it was found that such a person could not reach the lower edge of the container to exert any effective force at all.

Simulation Objective - To demonstrate effect of large/strong man (5%) on hand forces necessary to position food container F550 above freezers.

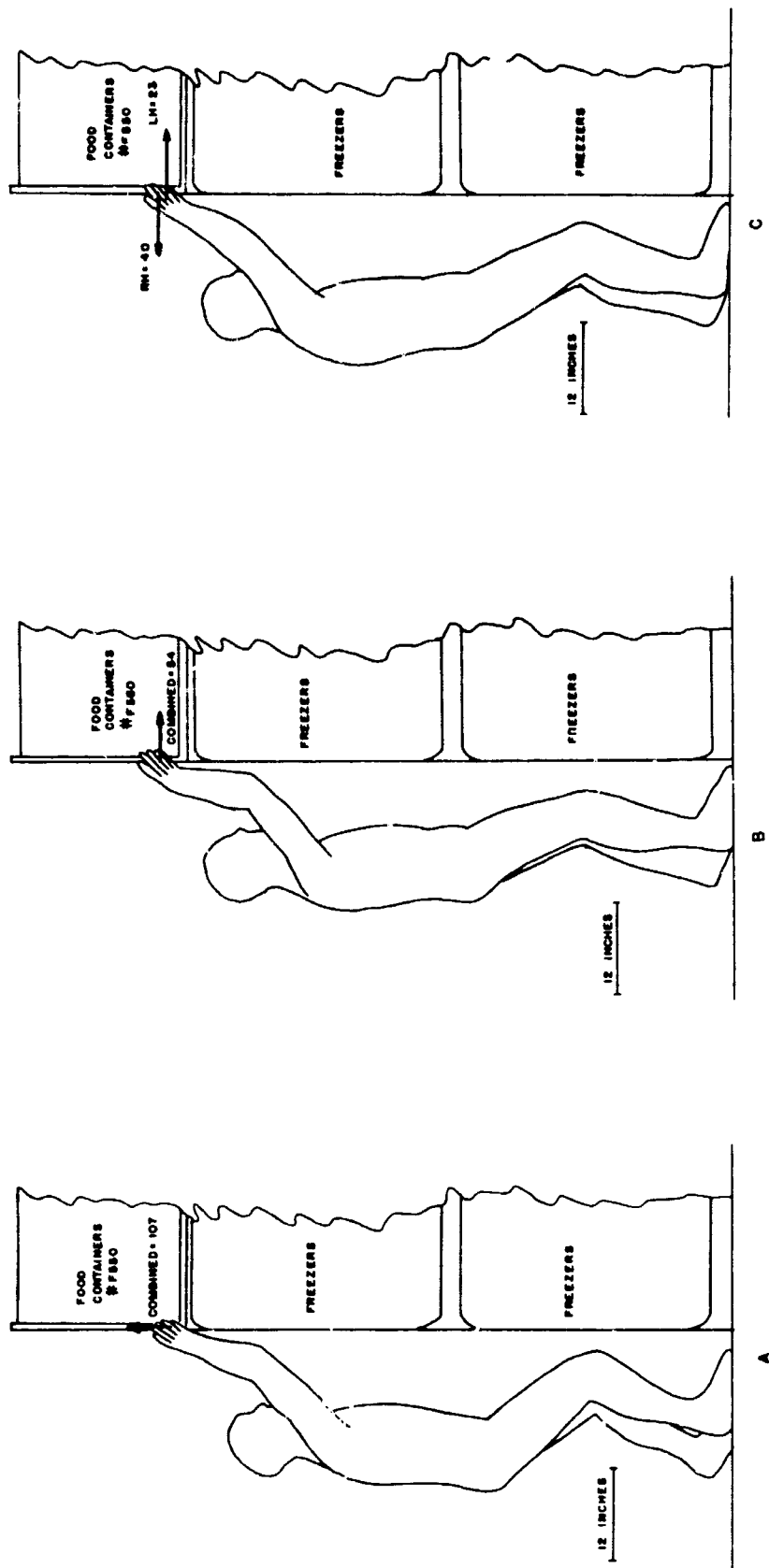


Figure 8 Large/Strong Man Positioning Food Container F550

It would therefore appear that a concerted effort should be expended to provide the means for better positioning of the feet (and associated portable foot restraint assemblies) than on the floor. It is suggested this would (1) conserve astronaut time in this task, (2) reduce the risk of impact damage to surrounding equipment, or (3) possibly avoid an injury to the astronaut involved in the container positioning task. A general rule to be followed in determining a better position from the biomechanics standpoint is that the hands be about 5 to 15 inches in front of the body and between knee and hip heights. Such a position would provide increases in the hand force capabilities of about four times of that depicted in Figures 7 and 8.

It is realized that providing another position for the feet which would increase the maximum hand force capability would greatly depend on cost considerations at this time, since hardware modifications are now so costly. Hopefully, some creative thinking during the training sessions will provide a method whereby the astronaut can lock his feet into some "non-standard" hardware to brace himself. It is obvious, however, that with a little more insight earlier in the design process this potentially serious problem could have been avoided.

Operating Trash Ejection Control Levers

The final simulation selected had to do with potential force problems that could arise from operating a mechanical linkage. In this case the mechanical lever action was involved in operating the trash ejector levers, wherein human force output is the primary and only means of utilizing the system. This task also was selected as it provided a demonstration of the ability of the model to simulate (and thus evaluate) two entirely different modes of operating the system. The first mode has the astronaut facing the controls in a manner wherein the main "dump" lever operates across the front of the torso. Figure 9 depicts the positions. The second mode has the astronaut standing at the side of the levers so that the "dump" lever operates towards the torso, as illustrated in Figure 10.

Again, various torso orientations were selectively simulated, using the average (50%) male anthropometric characteristics. The primary force of interest was the right hand capability to operate the "dump" lever. Over 200 arm and leg positions were attempted for each simulation.

Results of Trash Ejection Simulations. The results are depicted in Figures 9 and 10. What is clearly indicated is that by facing the control levers (as in Figure 9) a much higher right hand force can be developed

Simulation Objective - To demonstrate effects of various torso orientations when applying forces to trash ejection control levers while directly facing controls (i.e. main lever moves from left to right)

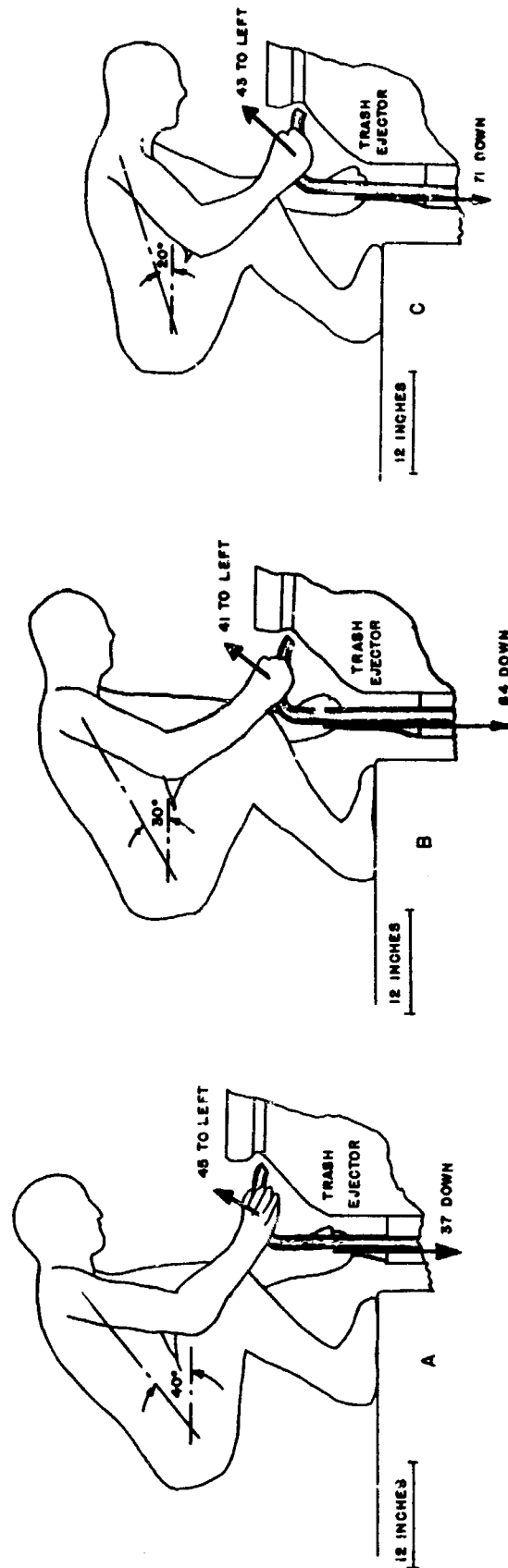


Figure 9 Operating Trash Ejection Control Levers - From Facing Position

Simulation Objective - To demonstrate effect of repositioning body (i.e. standing so as to have main lever move directly towards the body) on the hand force: with the torso oriented in both a horizontal (E) and semi-stooped (D) manner.

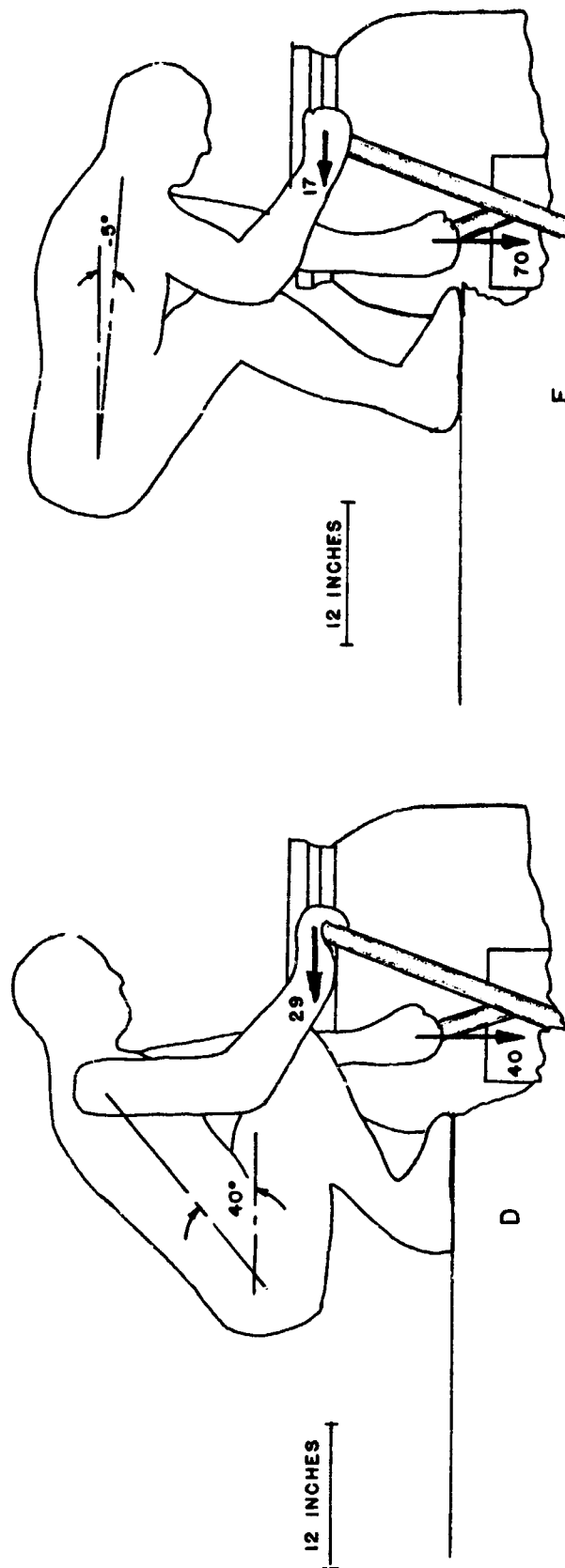


Figure 10 Operating Trash Ejection Control Levers - From Side Position

than when standing to the side (as in Figure 10). In addition, if a corresponding left hand force is needed it would appear that assuming a posture wherein the astronaut leans over the controls (as in Positions B and C in Figure 9) provides a higher force capability.

Once again, it is not expected that the trash ejector handles will require such high forces (a check of the Training Mockup at MSC showed an average eight pound force was required on the main lever). Rather, these results should be viewed as an evaluation of two extremely different modes of operation, one (Figure 10) that intuitively might seem good in that it is often recommended to have force controls operate towards the body, and another mode (Figure 9). As shown, for zero G the pulling force towards the body is lower in the intuitively recommended mode of operation depicted in Figure 10. This is due to the body weight not assisting in the pulling action as it would in one G. Thus the recommendation is to have the astronauts face the controls, as in Figure 9, and move the main control across the front of the body. Because of the larger capability in this position they would be expending less relative effort, and in the eventuality of an increase in the operating force requirements they would be in the best position for applying higher forces.

Summary of Force Simulations

The preceding human strength simulations have been completed to demonstrate the analysis capability of such an approach. In addition, it is hoped that direct benefits to the Skylab missions can be gained by some of the simulation results. Specifically it is believed that these results can:

1. Result in less physical effort (and metabolic energy) being expended to perform the tasks.
2. Reduce the time required to perform some of the tasks.
3. Reduce the risk of either impact damage to equipment or injury to an astronaut during the transfer of large masses.

At this point in the development of Skylab it is hoped that the results will assist in the development of operations procedures and training. It should be obvious, however, that the greatest benefit of such a simulation technique is in the earlier engineering design stages. As a partial step towards assisting the designer, a large set of one-handed strength simulations have been completed, and the results have been tabulated for easy reference in the next Section.

IV. Predicted Hand Forces For Seated Activities

This section is meant to assist in assessing the relative effects of hand positions and the associated body configurations on single-handed strengths. As such it is meant to be a reference section containing tabulated simulation results for various types of single-handed exertions and hand positions. Some general observations regarding how single-handed strengths vary are presented at the end of the section.

Criteria for Using Results

The results are applicable to the following situations:

1. Isometric (or very slow movement) exertions of no longer than four seconds duration with adequate rest between exertions.
2. Only the right hand is used to apply the force.
3. The astronaut is seated with his pelvis secured by a lap-belt.
4. The seat pan has a slight tilt (a 6° tilt was assumed) backwards from the horizontal, and the seat back is tilted backwards 13° from the vertical, (this latter constraint is not that important as explained in note 5.

5. The seat back assists in securing only the pelvis and not the entire torso, thus torso strength is relied upon to develop pushing forces. This allows evaluation of hand force capabilities when the astronaut is leaning forward away from the seat back to reach a specific control position.
6. All exertions are in zero G conditions.

It is suggested that the recent excellent empirical studies of Thordsen, Kroemer, and Lauback also be consulted for additional seated hand force data.¹ Their study summarizes actual hand forces developed by a young male population assuming a set of specific hand positions. They also assumed a full seat back with no lap or shoulder restraints, thus producing design data that augments this presentation.

Method of Interpreting Tables

The following tables contain two types of information as a function of the hand-to-hip coordinates. First and most important, the right hand isometric force prediction (in pounds of force) is given. Below that at each selected hand position is a code designating the gross body configuration associated with the hand force. This coding scheme is further explained in the following subsection.

¹Thordsen, M.L., K.H.E. Kroemer, and L.L. Laubauck, Human Force Exertions in Aircraft Control Locations, AMRL-TR-71-119, Wright-Patterson AFT, Ohio, 1972

Interpretation of body configuration code. The body configuration code provides information pertaining to the gross body configuration, as referenced by four angles. These are: 1) shoulder vertical angle; 2) elbow included angle; 3) included hip angle; and 4) torso lateral bending angle. The first two components of the code are numbers ranging from one to six regarding the right arm configuration. The second two components are letters intended to describe the general torso configuration. The letters and numbers represent the following conditions and angle ranges:

Code	Shoulder Vertical Angle from Axis Connecting both Shoulders			Code	Elbow Included Angle Between Segment		
1	-90°	→	-60°	1	20°	→	50°
2	-60°	→	-30°	2	50°	→	75°
3	-30°	→	0°	3	75°	→	100°
4	0°	→	+30°	4	100°	→	125°
5	+30°	→	+60°	5	125°	→	150°
6	+60°	→	+90°	6	150°	→	180°

Code	Torso Sagittal Plane Angle from Vertical Axis			Code	Torso Frontal Plane Angle from Vertical Axis		
H (hyper-flexed)	30°	→	50°	L (Left)	-30°	→	-5°
F (flexed)	50°	→	75°	N (Neutral)	-5°	→	+5°
E (Erect)	75°	→	110°	R (Right)	+5°	→	+30°

For example, a code of 2-4-H-L would indicate that the shoulder vertical angle is between -60° and -30°, elbow

included angle is between 100° and 125° , the trunk is hyperflexed, and the trunk is leaning towards the left. Figure 11 further describes the code with another example.

It should be noted in referring to these body configuration codes that they are the result of iterating the body angles through various feasible positions while searching for the single greatest hand force capability. It has been determined by recent unpublished studies of these investigators that the highest strength positions for different individuals are not the same. Therefore, the recommended body configurations in this report must be viewed as one of many potentially good strength configurations, and not as the only good configuration. In fact, on an average when people are allowed to achieve their "freely chosen" configuration, they perform as well or slightly better than when placed in the configuration recommended by the model. Thus the model could be considered to give conservative strength estimates.

Order of Presentation of Simulation Results

Two different populations were used in the strength simulations. These were based on the average male and small/weak male (50% and 95% in the earlier Tables I and II, respectively). By referring to the two population strengths the person using these data can ascertain a degree of confidence in applying the data to a specific population. For instance, often the more conservative 95%

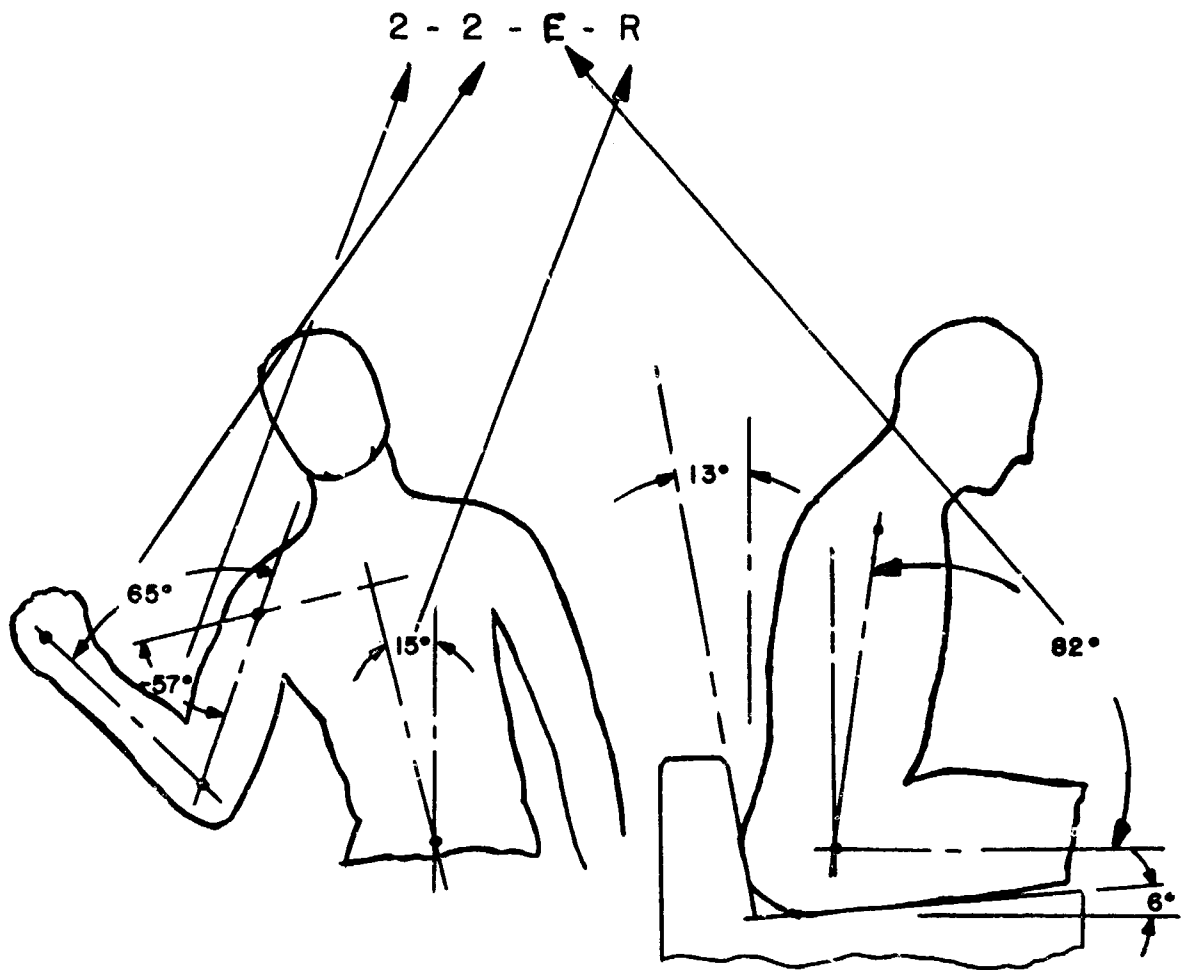


FIGURE II

ILLUSTRATION OF BODY CONFIGURATION CODE

data is used in design situations if it cannot be determined that the population contains specifically higher strength individuals.

The presentation of the data follows this division of the population, since the decision as to which population data is appropriate can be made prior to any specific design problem. Thus the first set of data (pages 51 to 68) is based on the average male, while the second set (pages 69 to 86) applies to the small/weak male.

Within each population division the following six types of exertions were simulated (with the order of reporting being the same):

1. Lifting-up
2. Pulling-down
3. Pulling-in
4. Pushing-out
5. Pulling-across (right-to-left)
6. Pulling-across (left-to-right)

The simulation results are reported using three hand heights above the hips. These are at 10, 20 and 30 inches. At each one of these heights 35 different hand positions were inputted, using the reach spheres of Kennedy (1964) to initially estimate the farthest reach points. (Because the Kennedy data did not allow torso assistance, some distances were attempted that were outside his projections. All the hand coordinates displayed in each table are

measured from the center of a line connecting the hip joints. Based on the recent study by Snyder, Chaffin, and Schutz (1972), this reference point could be estimated to be 4.0 inches above the 3.6 inches in front of the often used Seat Reference Point for the average sized young male. The order of reporting is to present the lower 10 inch data plane first, followed by the 20 inch and 30 inch high planes.

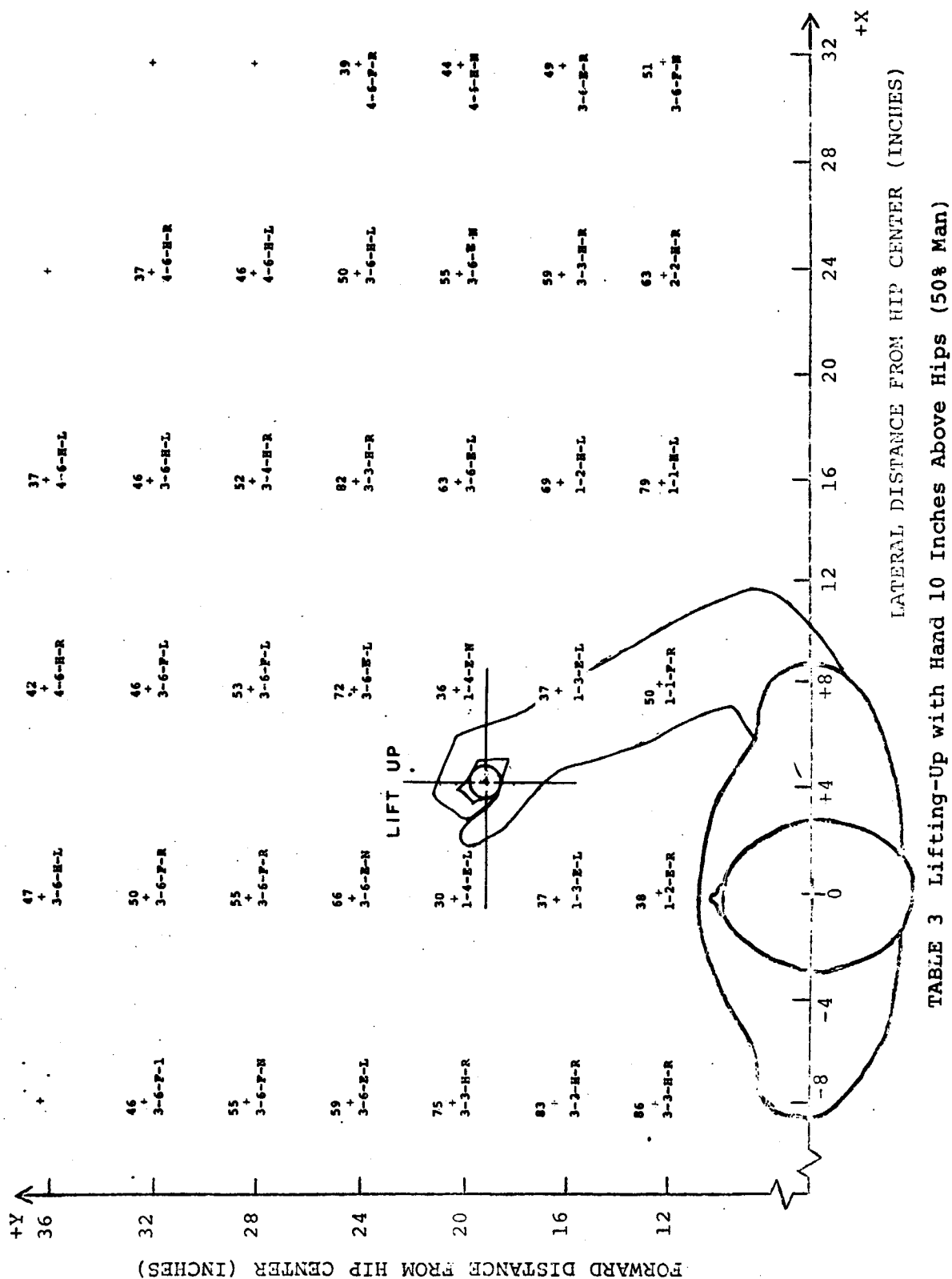


TABLE 3 Lifting-Up with Hand 10 Inches Above Hips (50% Man)

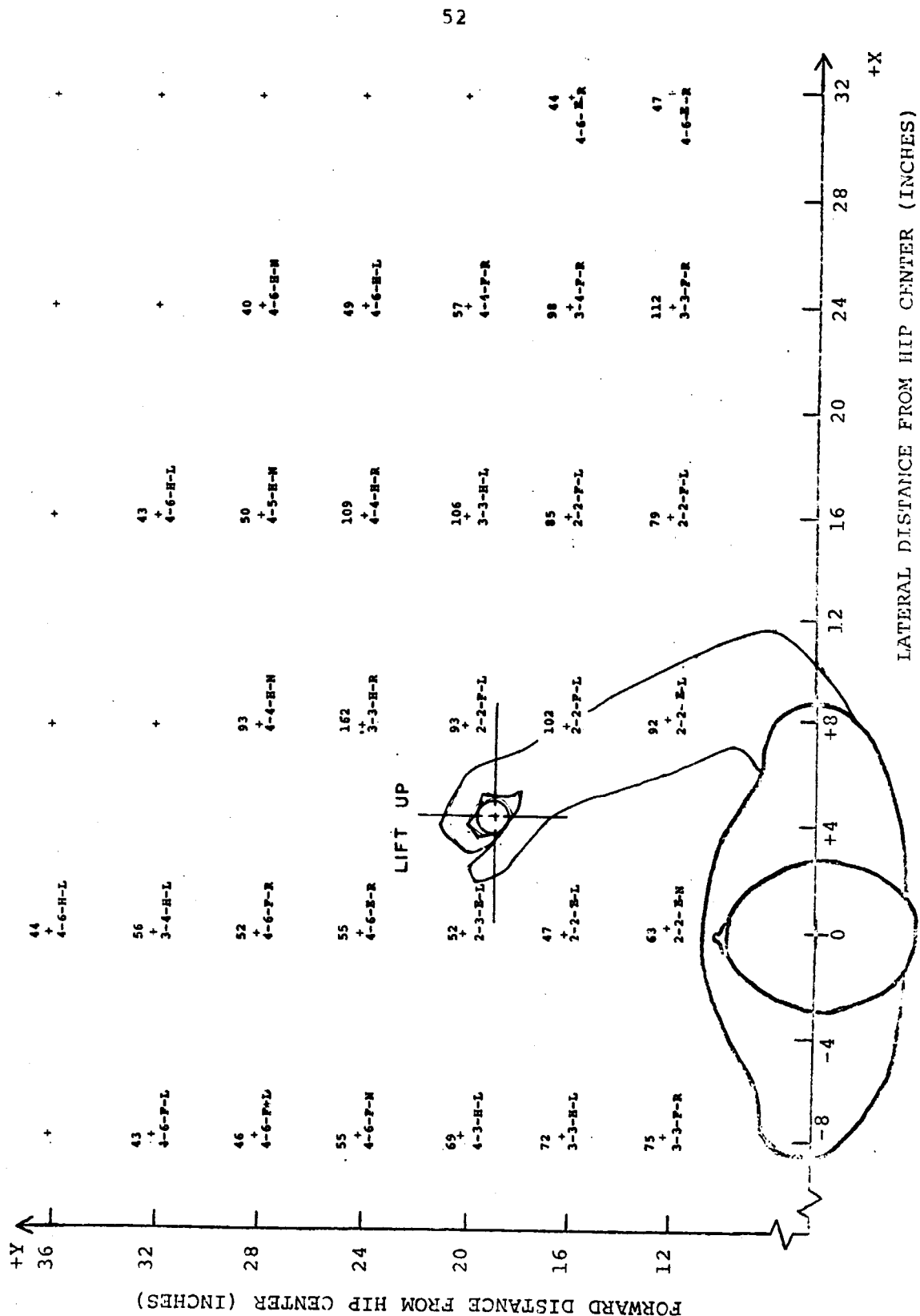


TABLE 4 Lifting-Up with Hand 20 Inches Above Hips (50% Man)

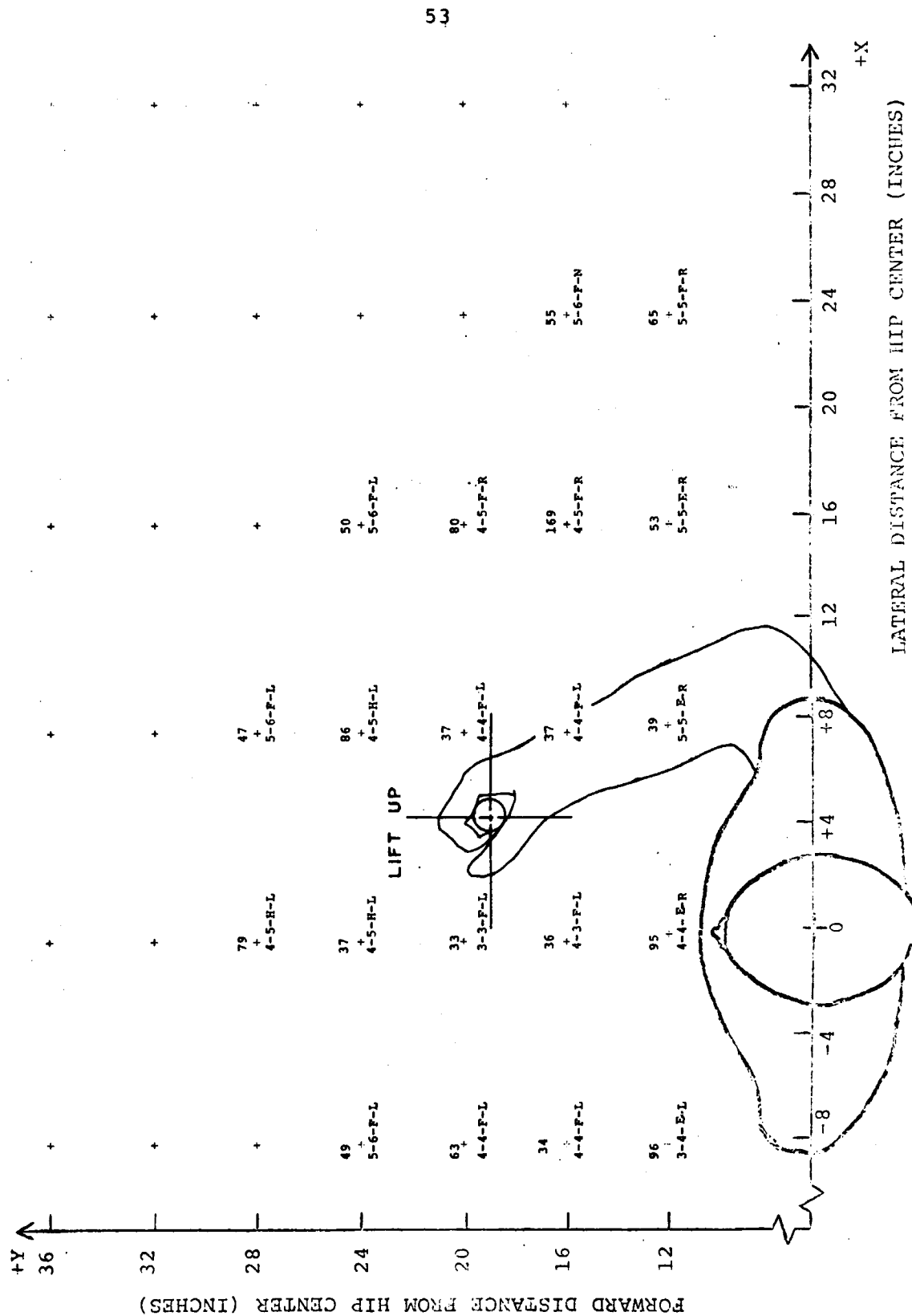


TABLE 5 Lifting-Up with Hand 30 Inches Above Hips (50% Man)

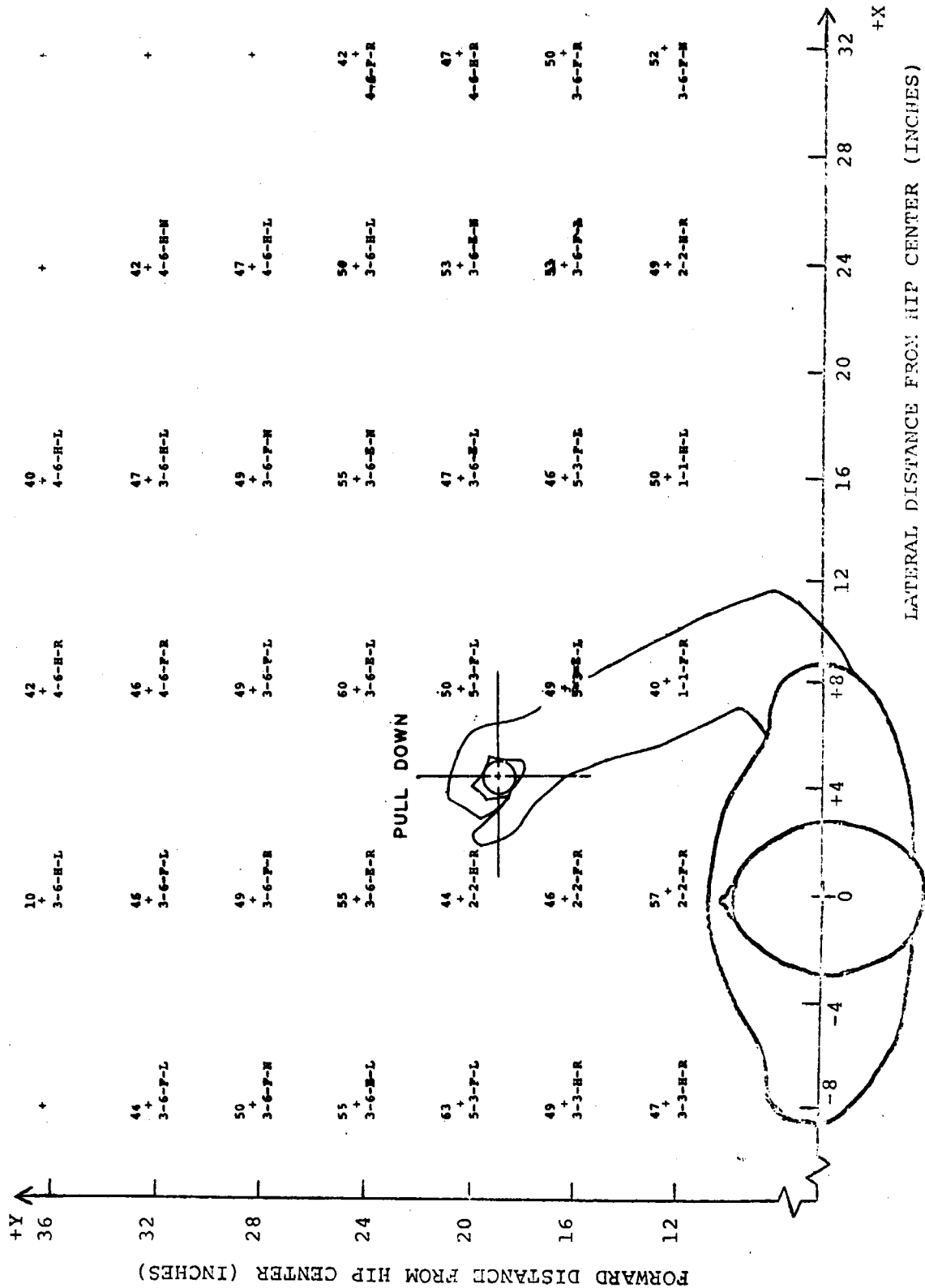


TABLE 6 Pulling-Down with Hand 10 Inches Above Hips (50% Man)

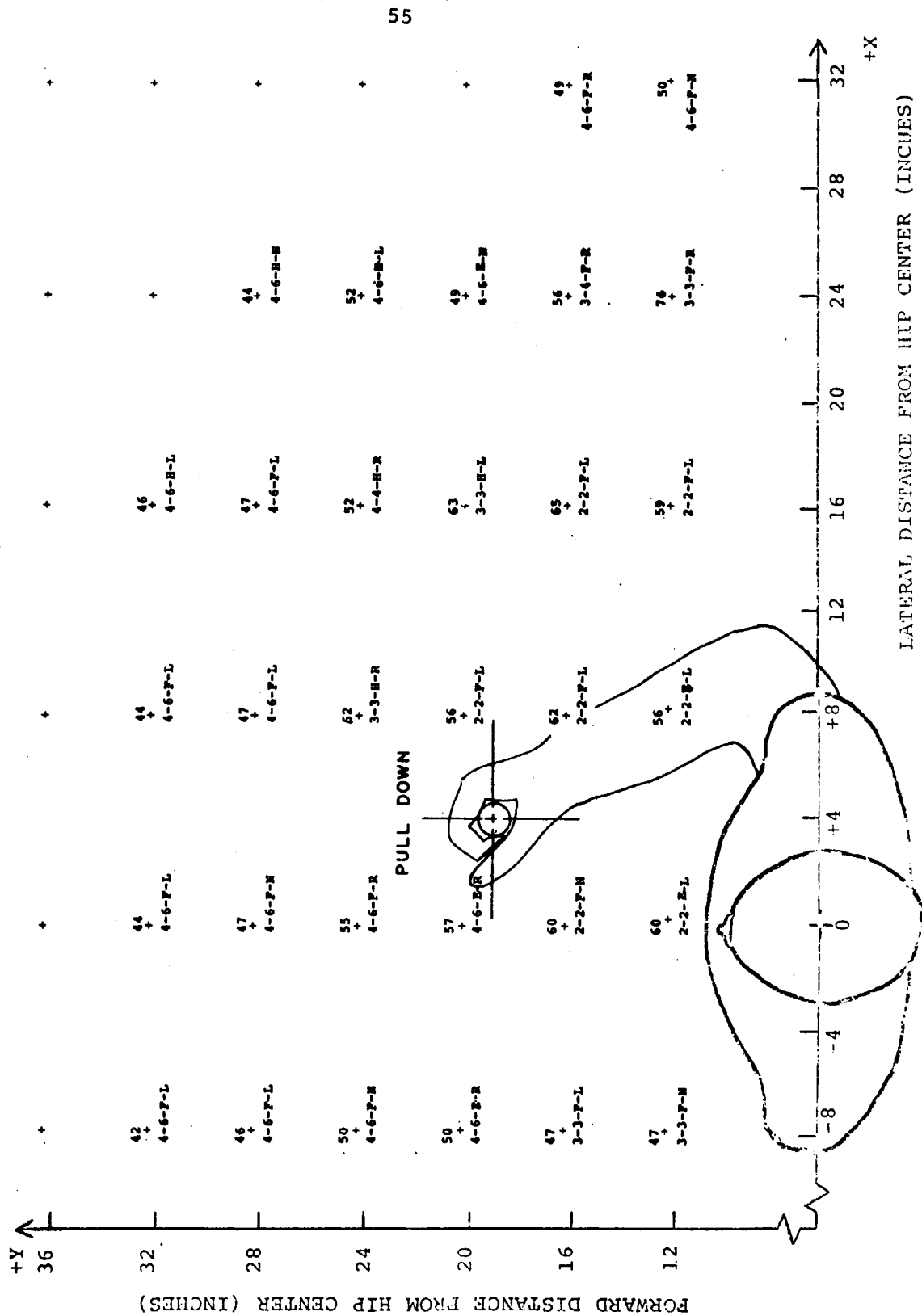


TABLE 7 Pulling-Down with Hand 20 Inches above Hips (50% Man)

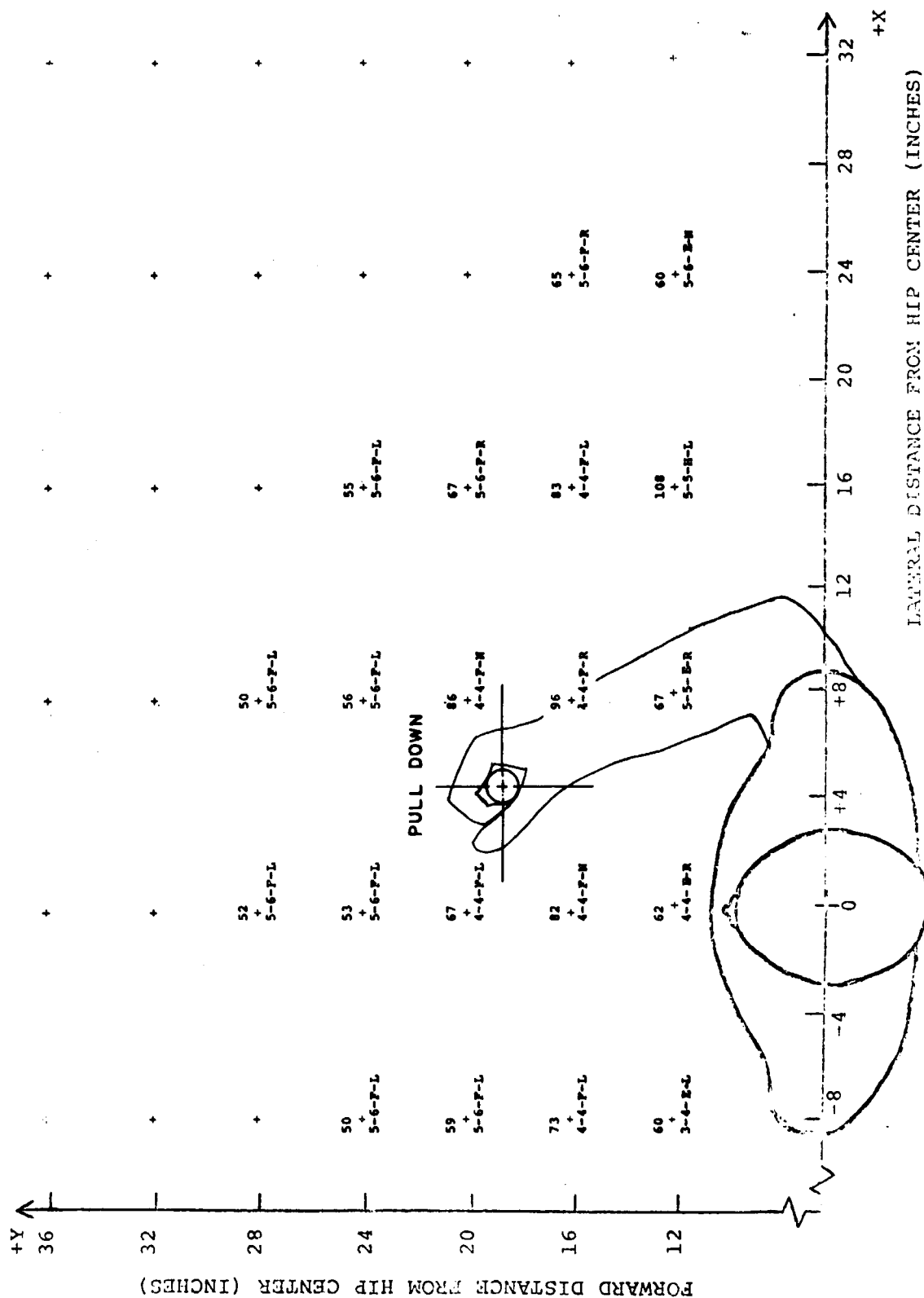


TABLE 8 Pulling-Down with Hand 30 Inches Above Hips (50% Man)

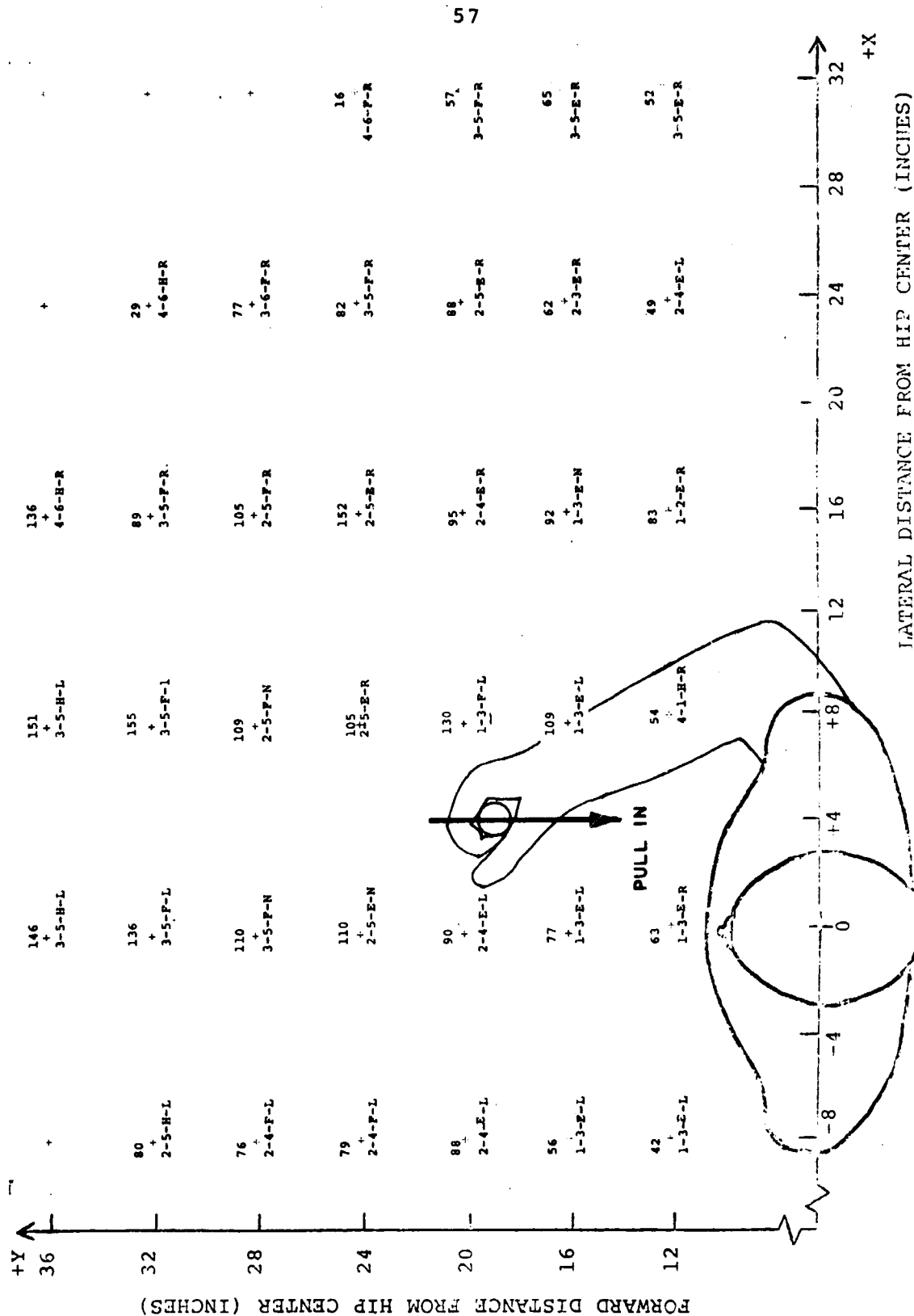


TABLE 9 Pulling-In with Hand at 10 Inches Above Hips (50% Man)

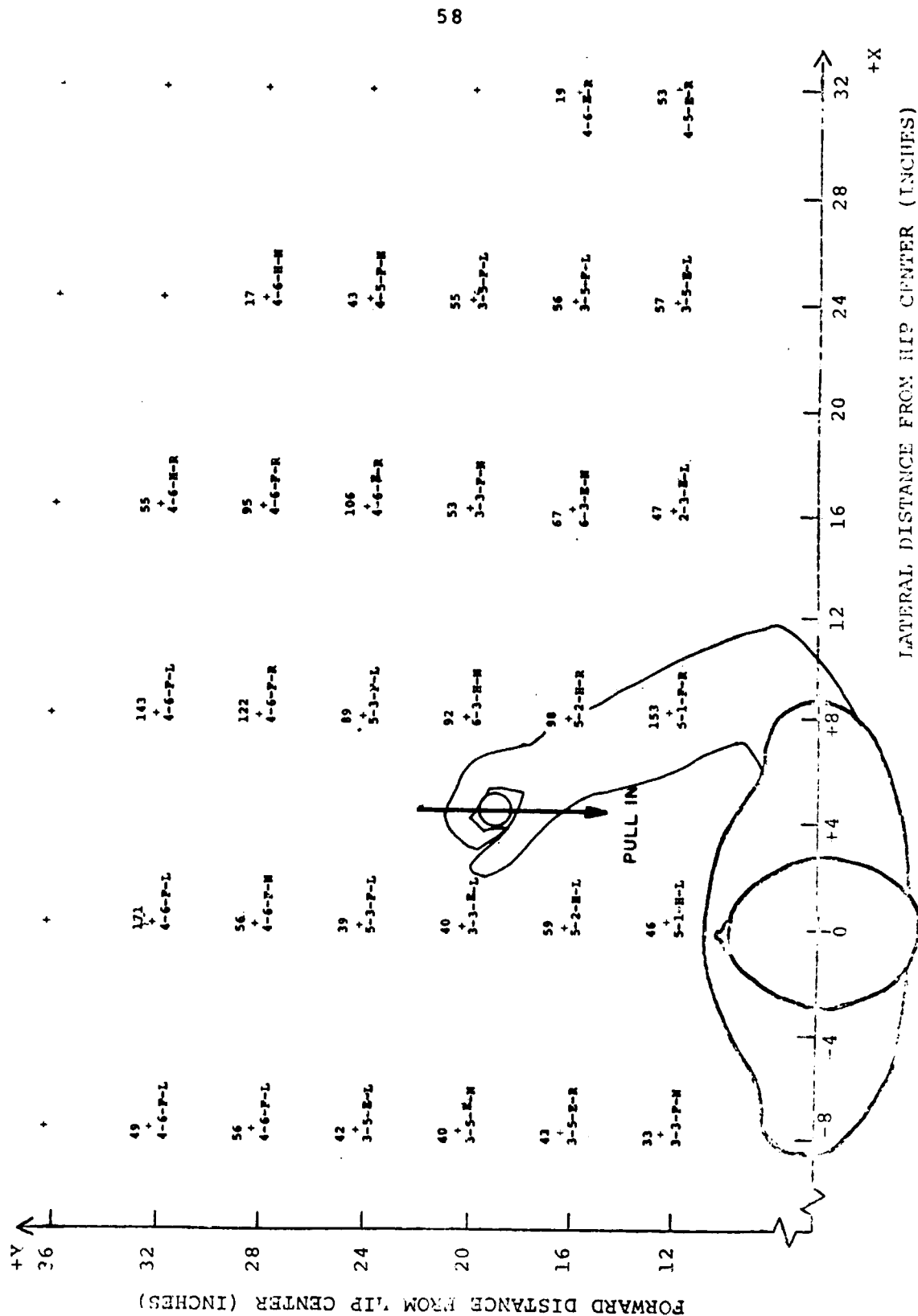


TABLE 10 Pulling-In with Hands at 20 Inches above Hips (50% Man)

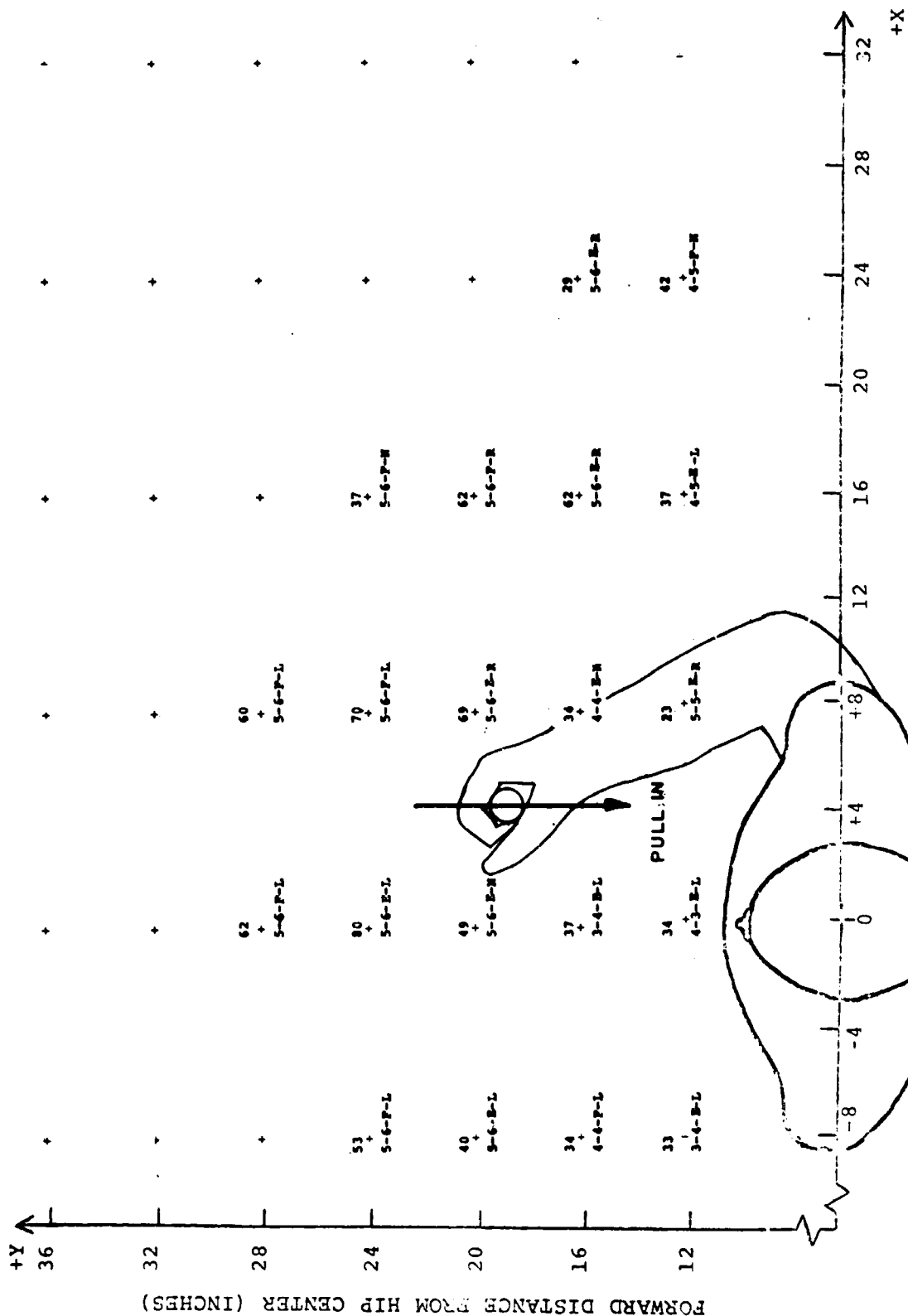


TABLE 11 Pulling-In with Hand at 30 Inches above Hips (50% Man)

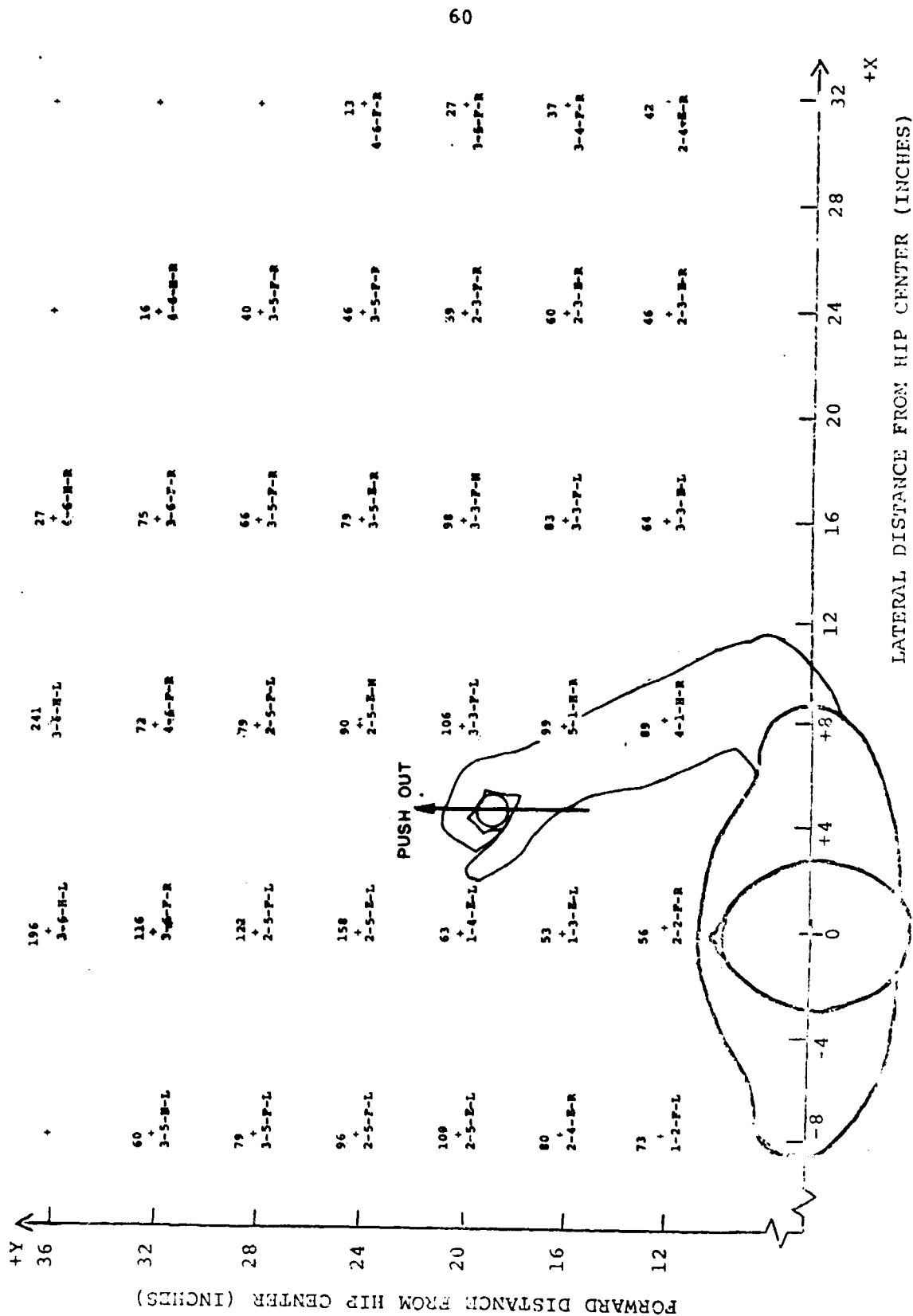


TABLE 12 Pushing-Out with Hand at 10 Inches above Hips (50% Man)

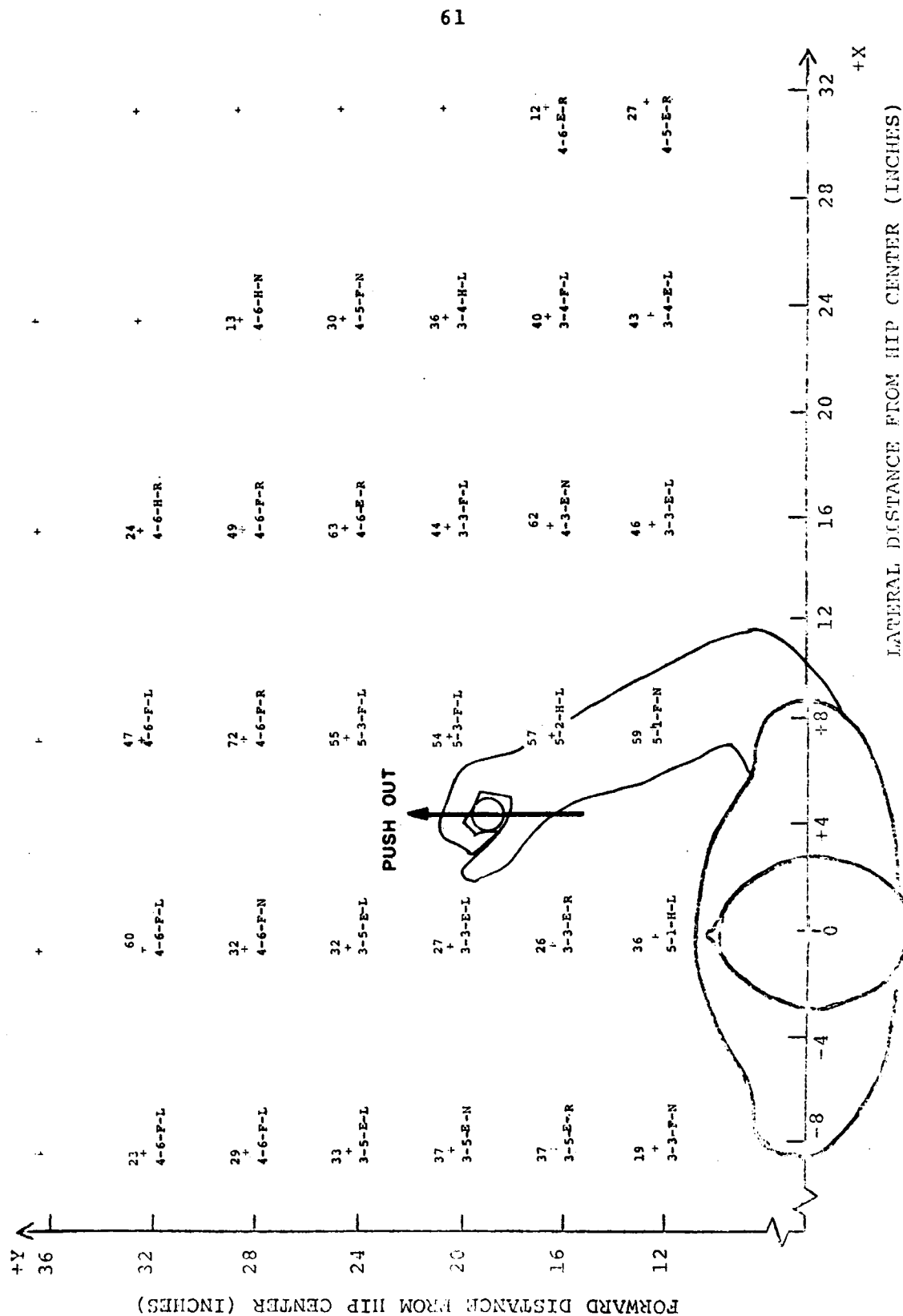


TABLE 13 Pushing-Out with Hand at 20 Inches above Hips (50% Man)

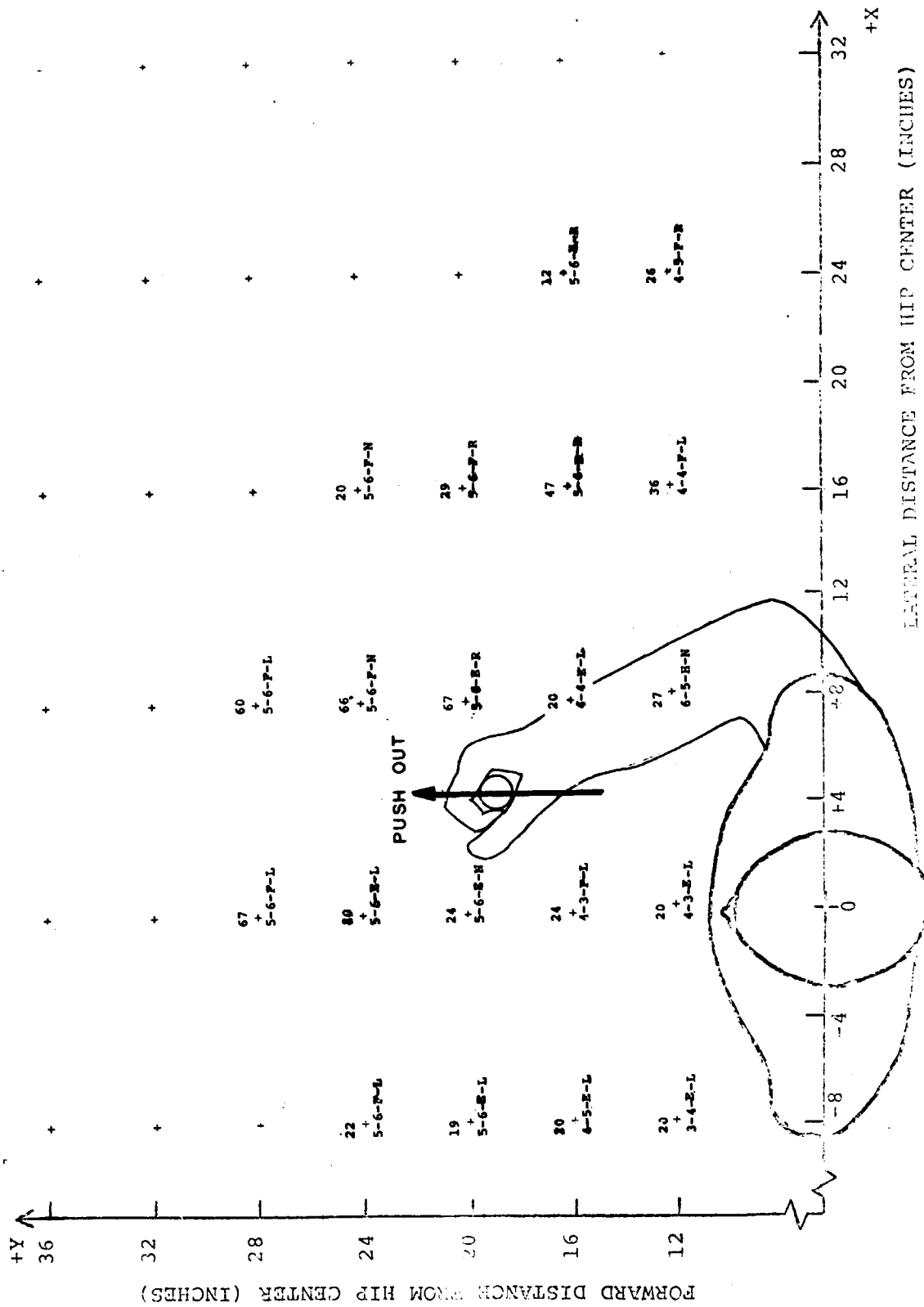


TABLE 14 Pushing-Out with Hand at 30 Inches Above Hips (50% Man)

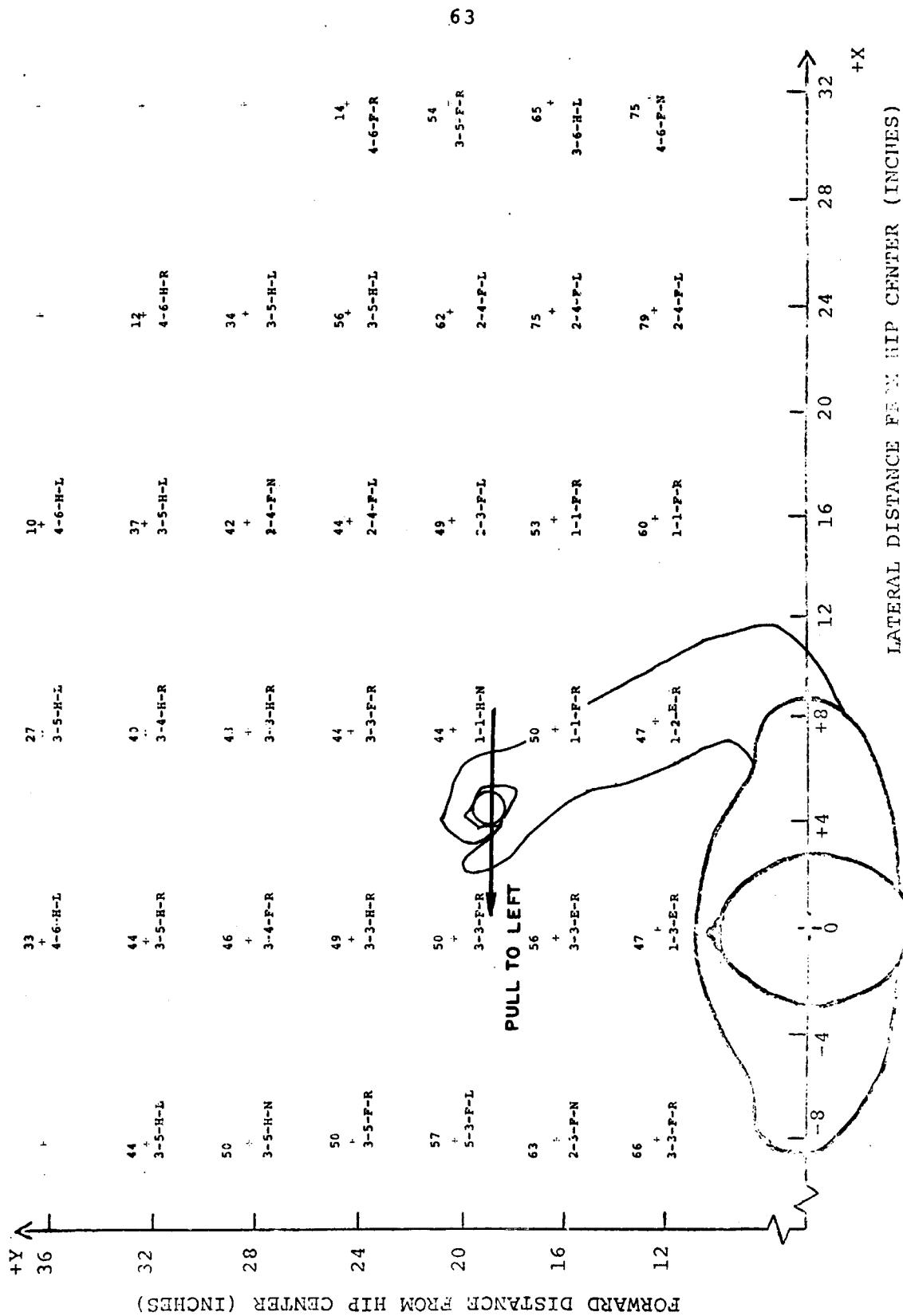


TABLE 15 Pulling-Across (right-to-left) with Hand 10 Inches Above Hips (50% Man)

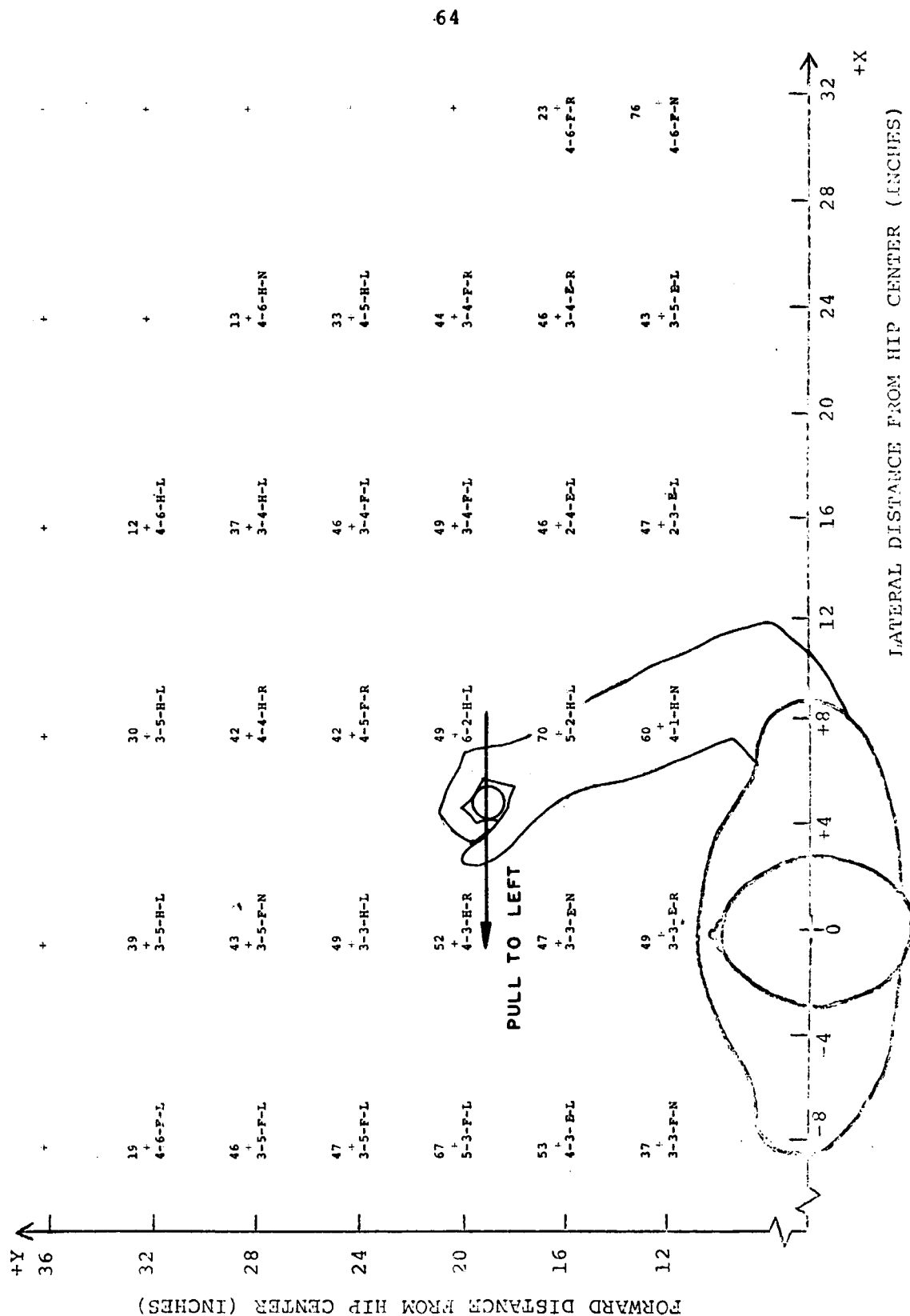


TABLE 16 Pulling-Across (right-to-left) with Hand 20 Inches Above Hips (50% Man)

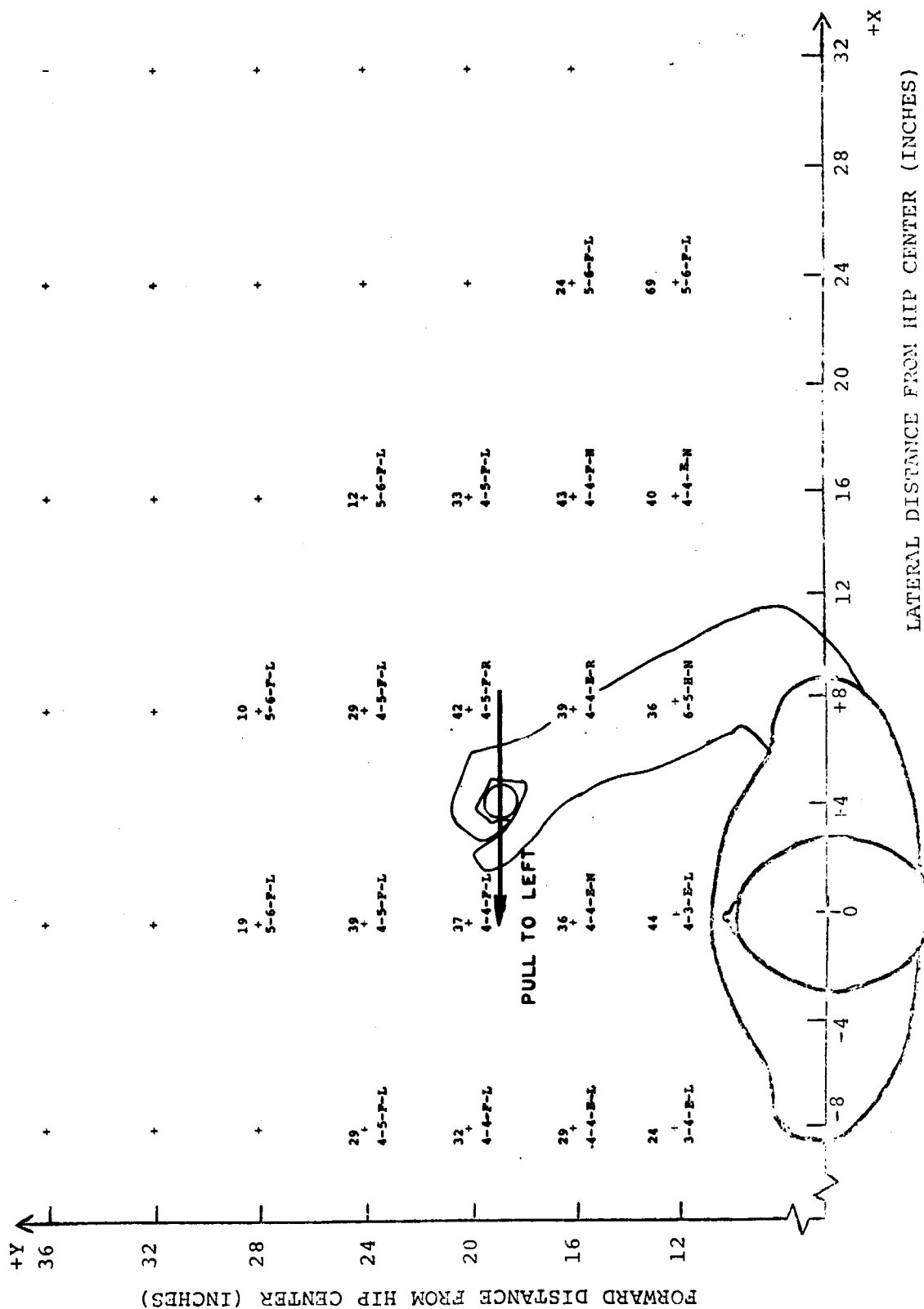


TABLE 17 Pulling-Across (right-to-left) with Hand 30 Inches Above Hips (50% Man)

TABLE 18 Pulling-Across (left-to-right) with Hand 10 Inches Above Hips (50% Man)

TABLE 19 Pulling-Across (left-to-right) with Hand 20 Inches Above Hips (50% Man)

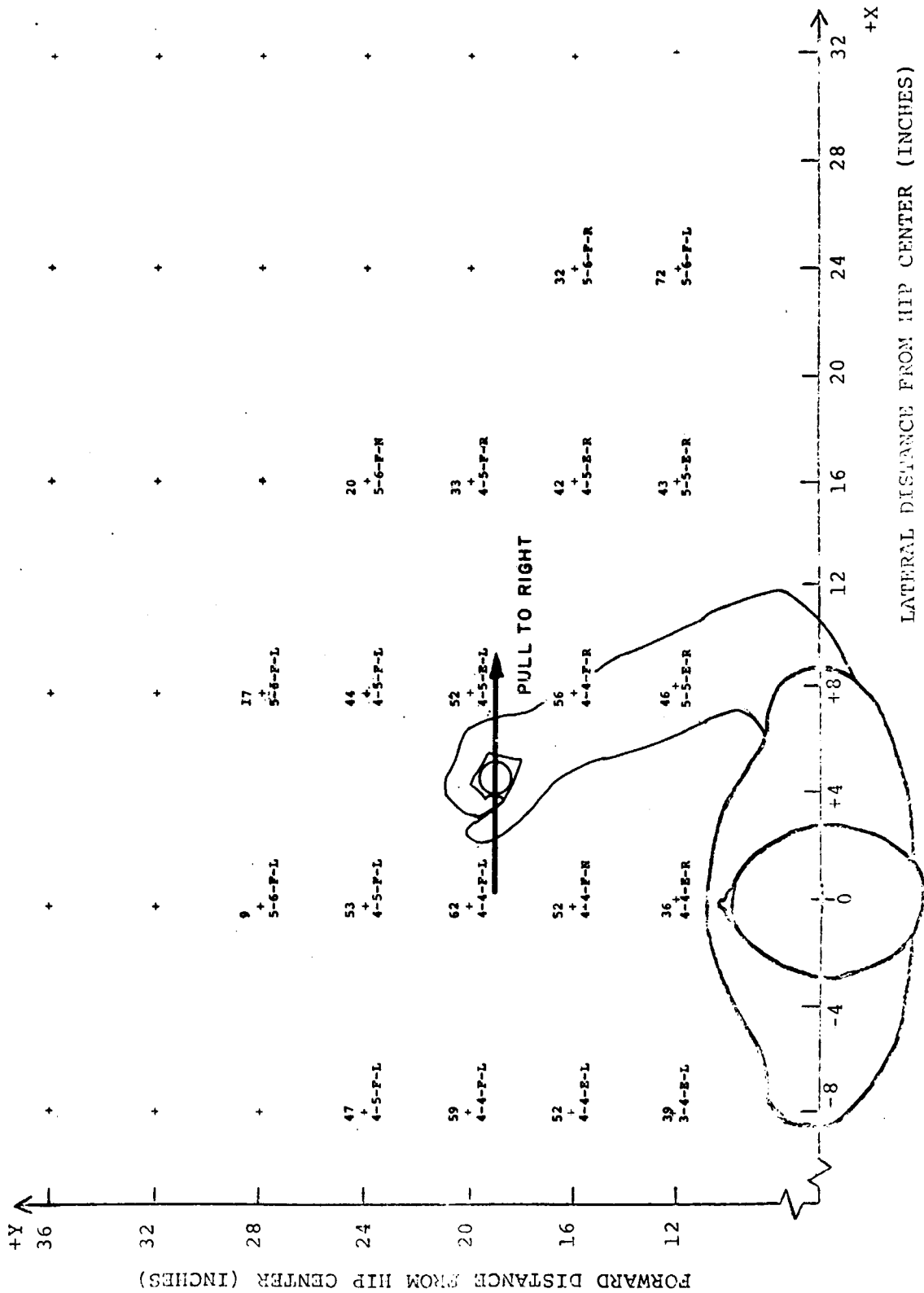


TABLE 20 Pulling-Across (left-to-right) with Hand 10 Inches Above Hips (50% Man)

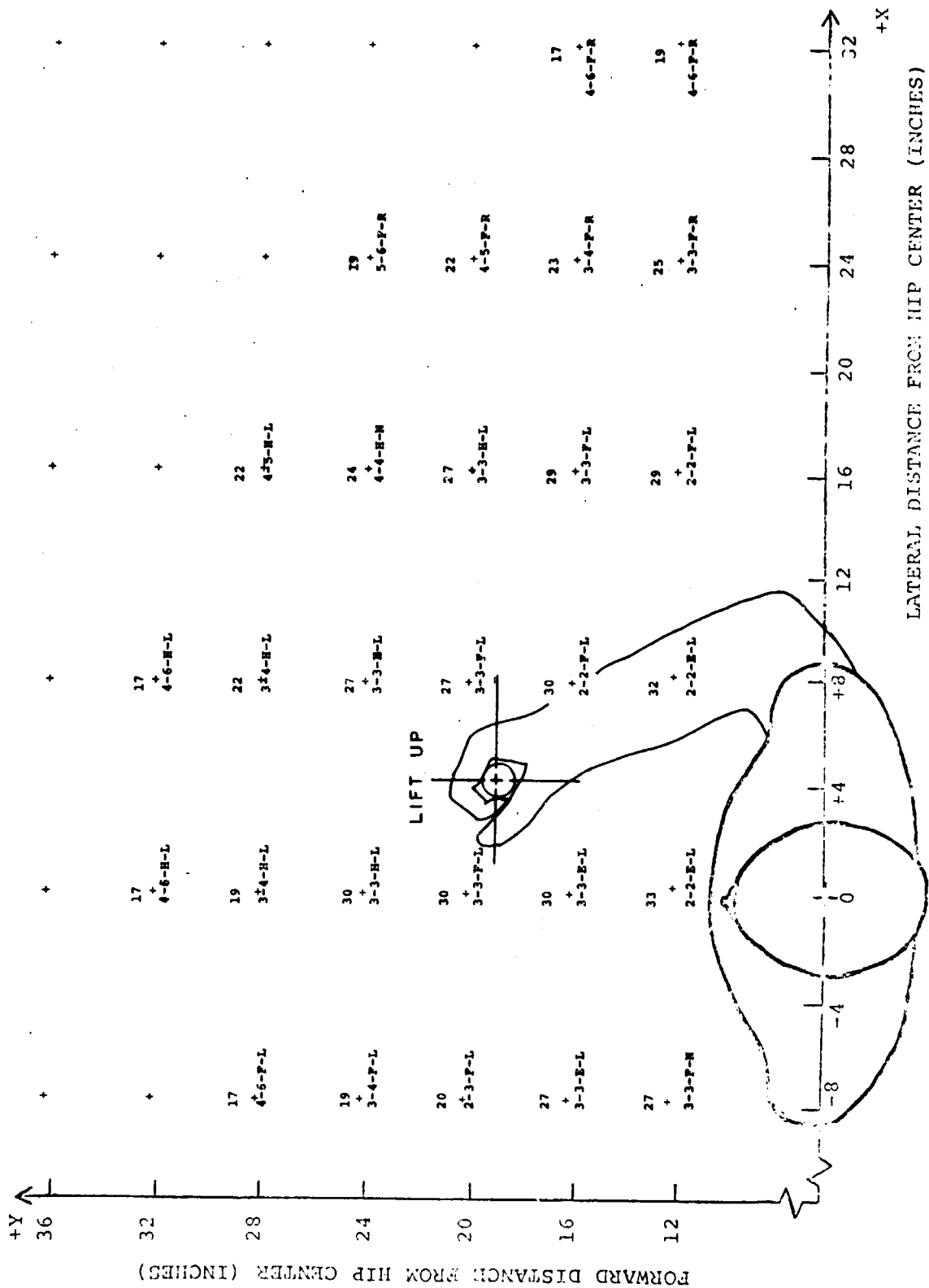


TABLE 22 Lifting-Up with Hand 20 Inches Above Hips (95% Man)

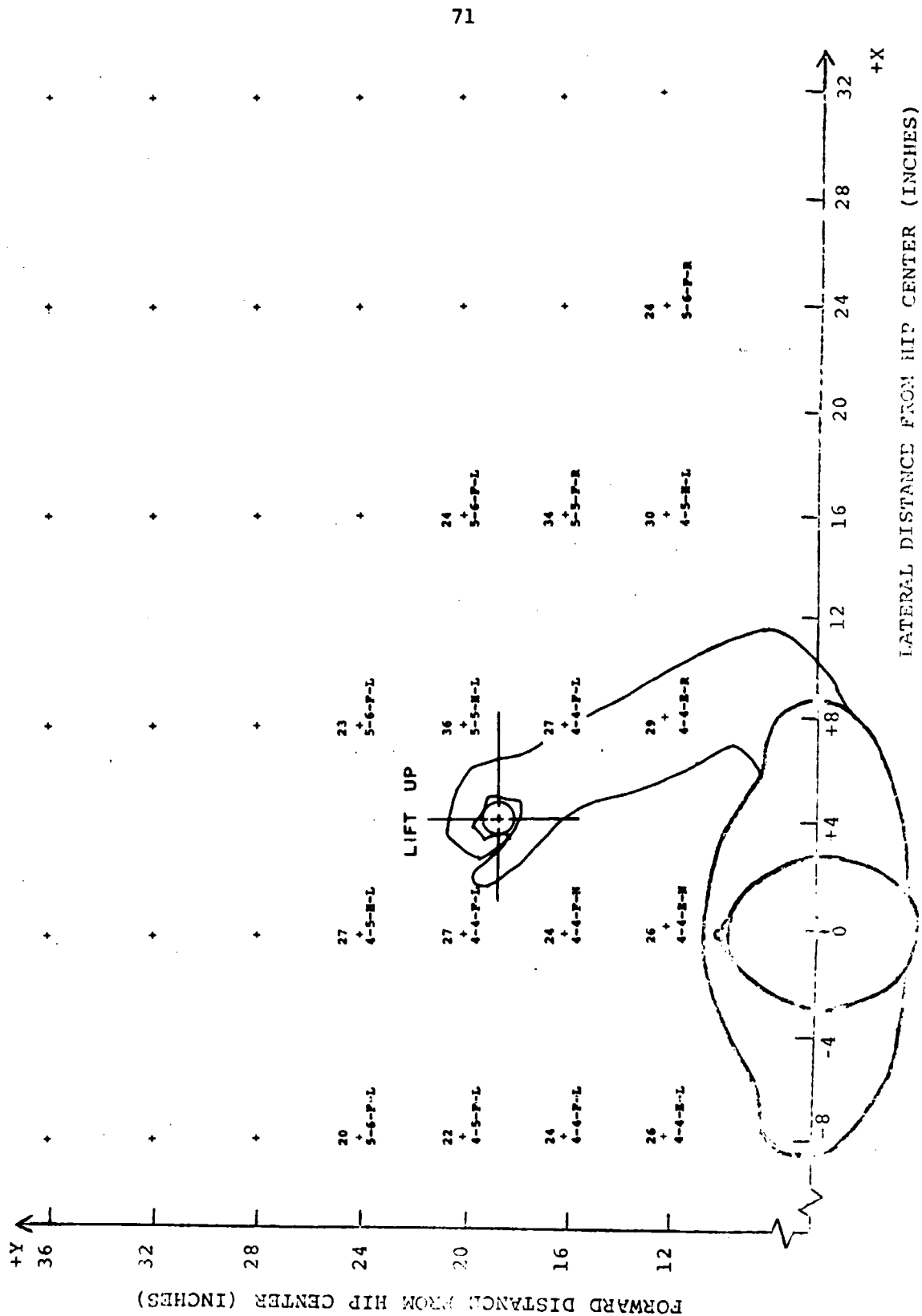


TABLE 23 Lifting-Up with Hand 30 Inches Above Hips (95% Man)

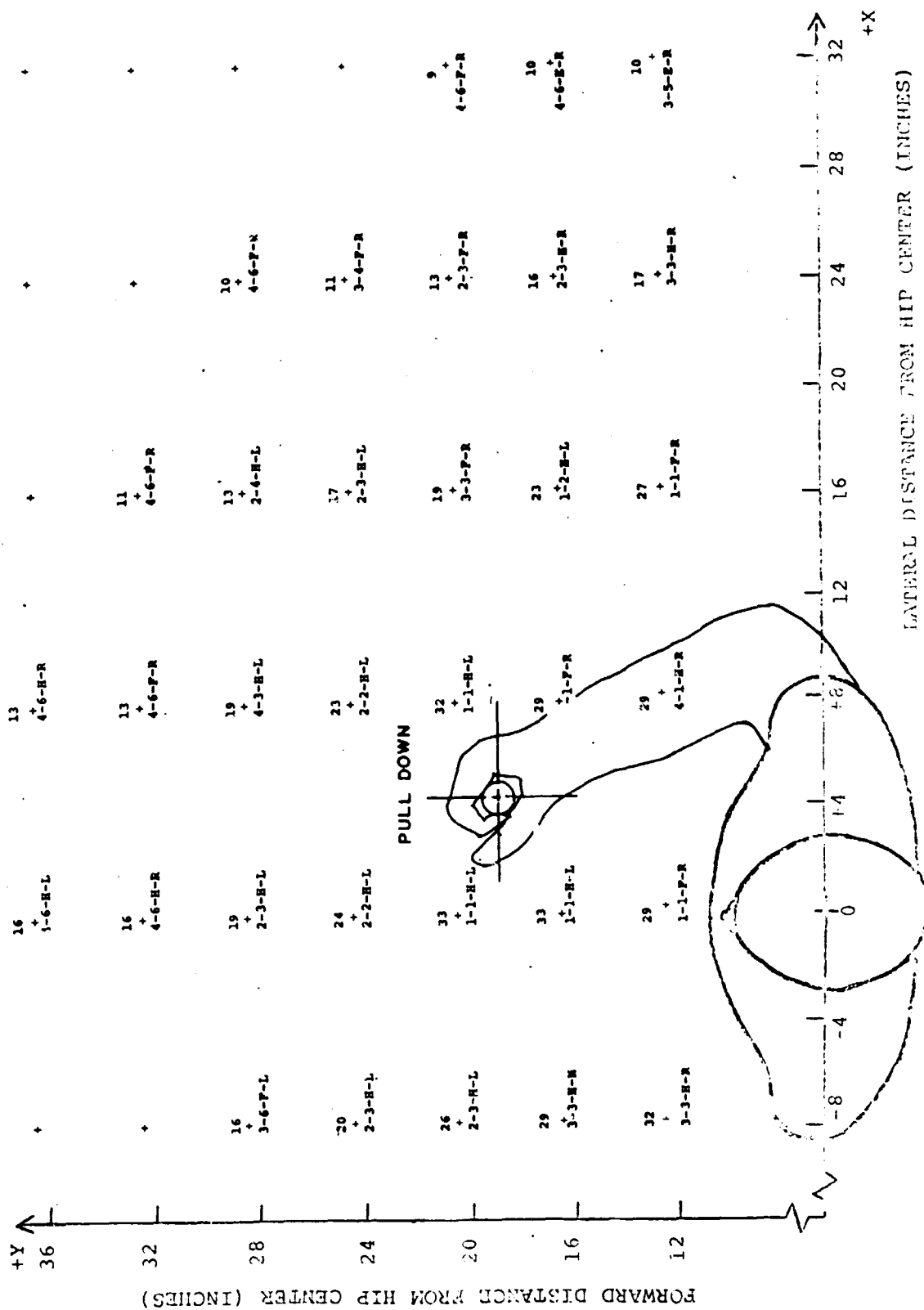
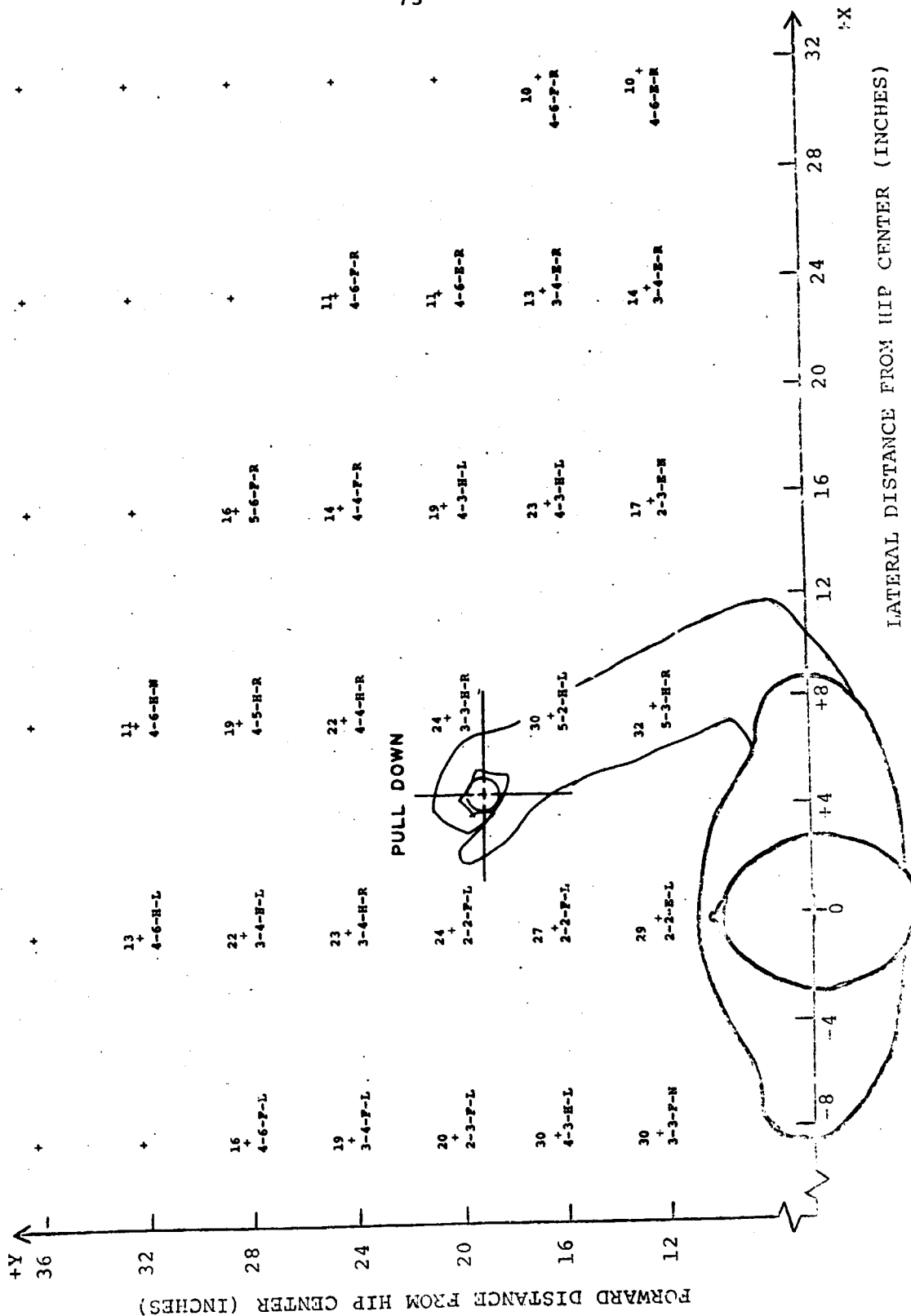
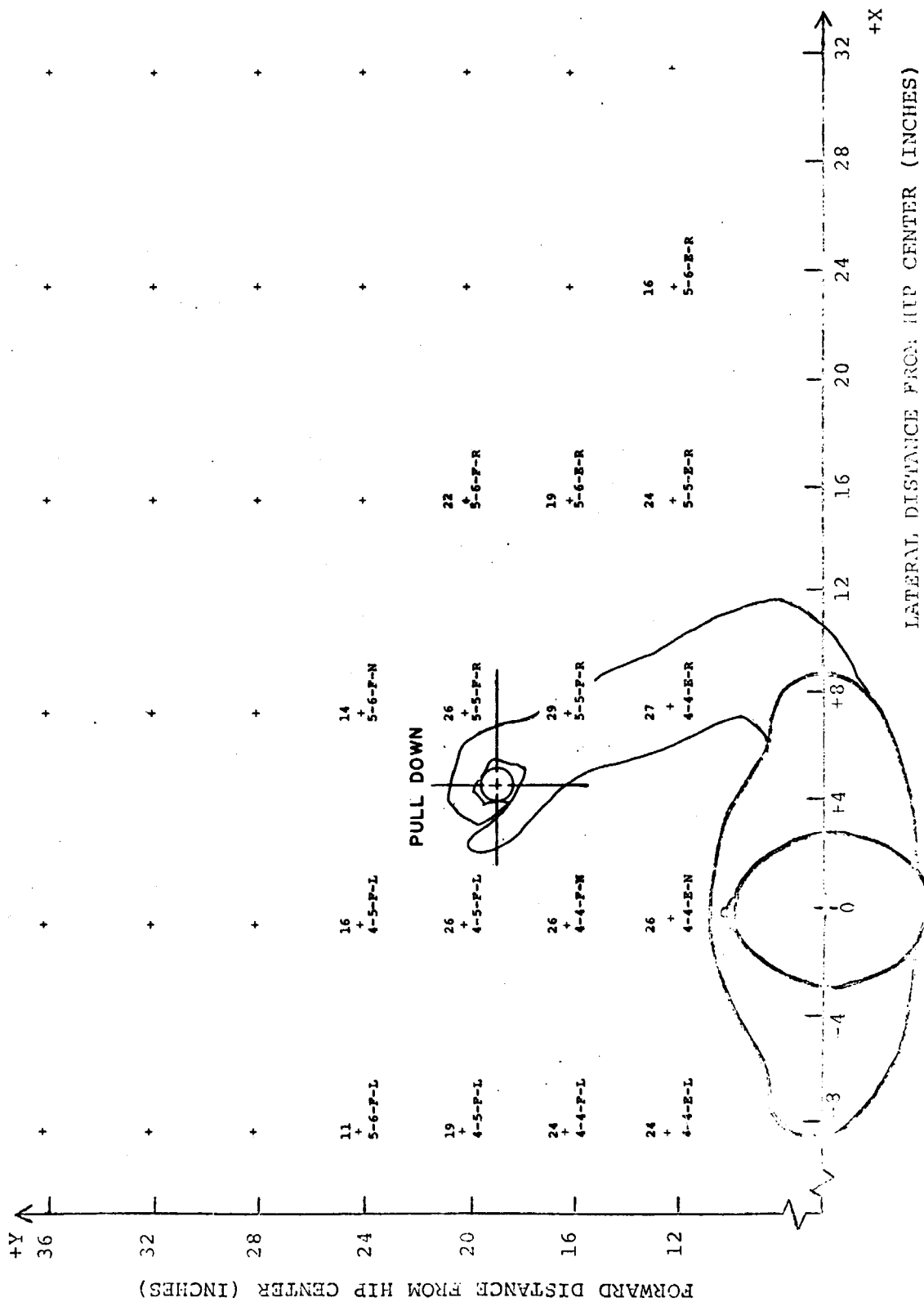
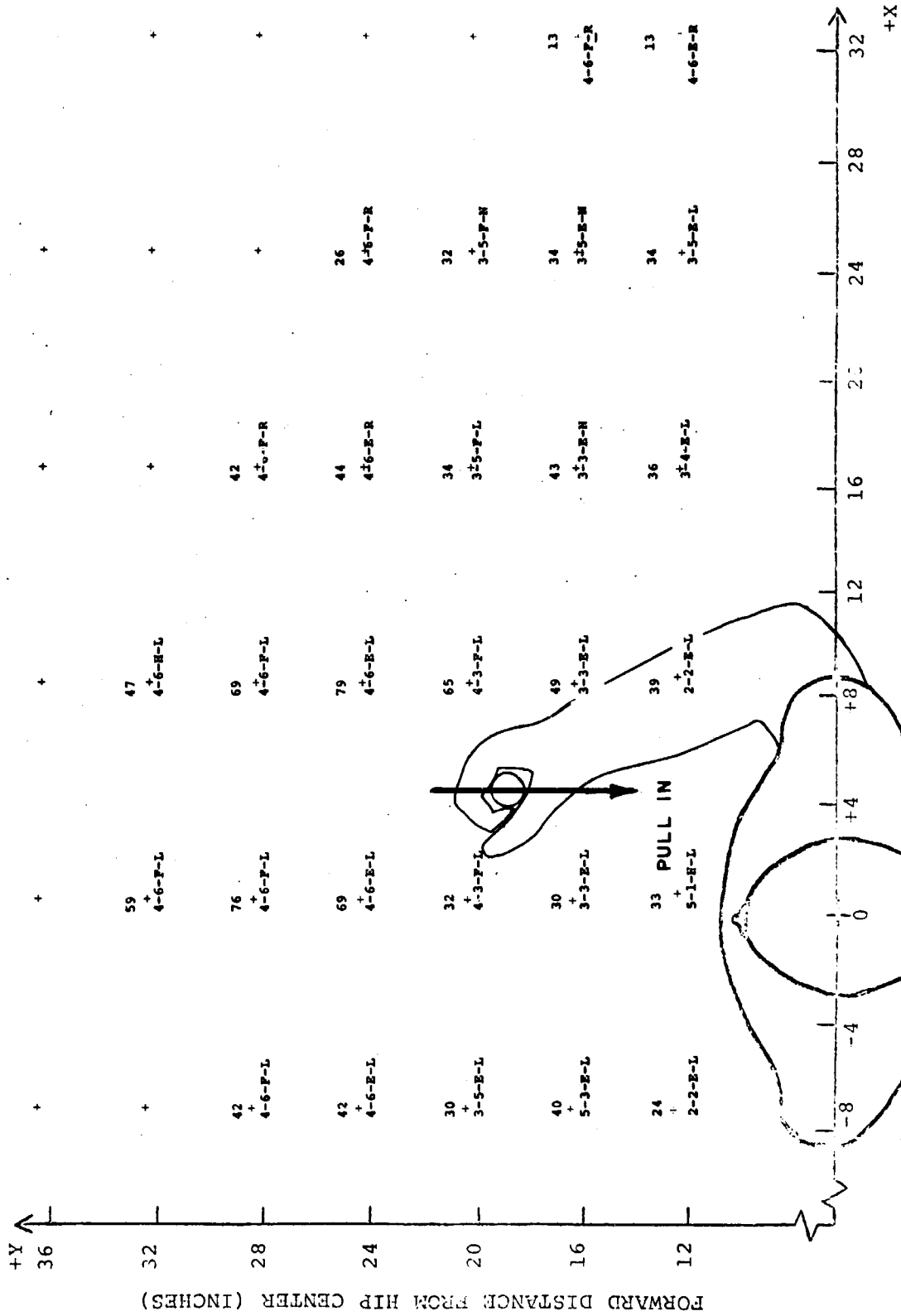


TABLE 24 Pulling-Down with Hand 10 Inches Above Hips (95% Man)







LATERAL DISTANCE FROM HIP CENTER (INCHES)

TABLE 28 Pulling-In with Hand at 20 Inches above Hips (95% Man)

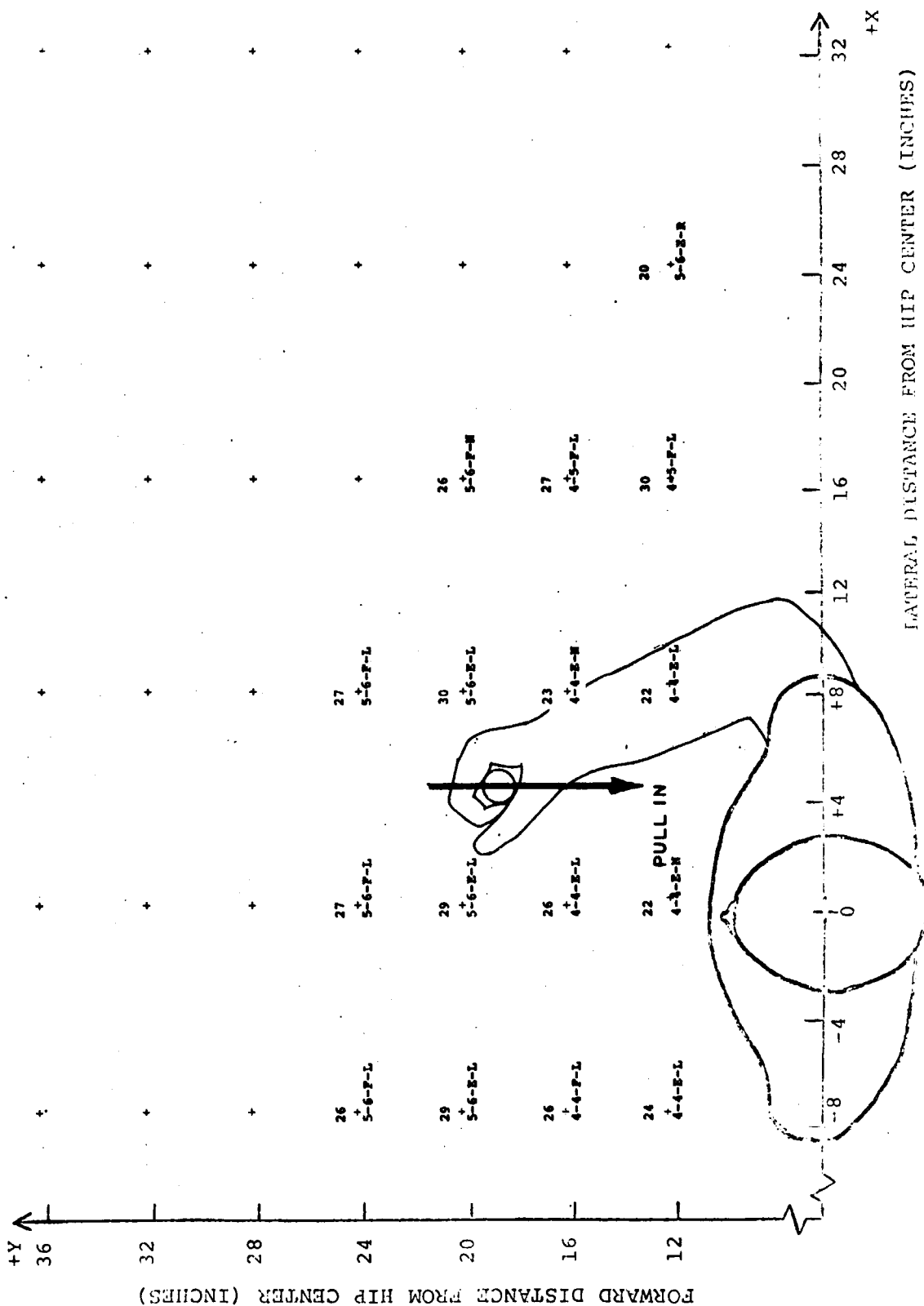
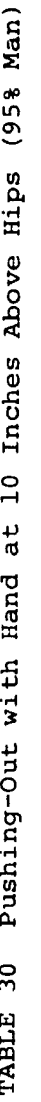


TABLE 29 Pulling-In with Hand at 30 Inches above Hips (95% Man)



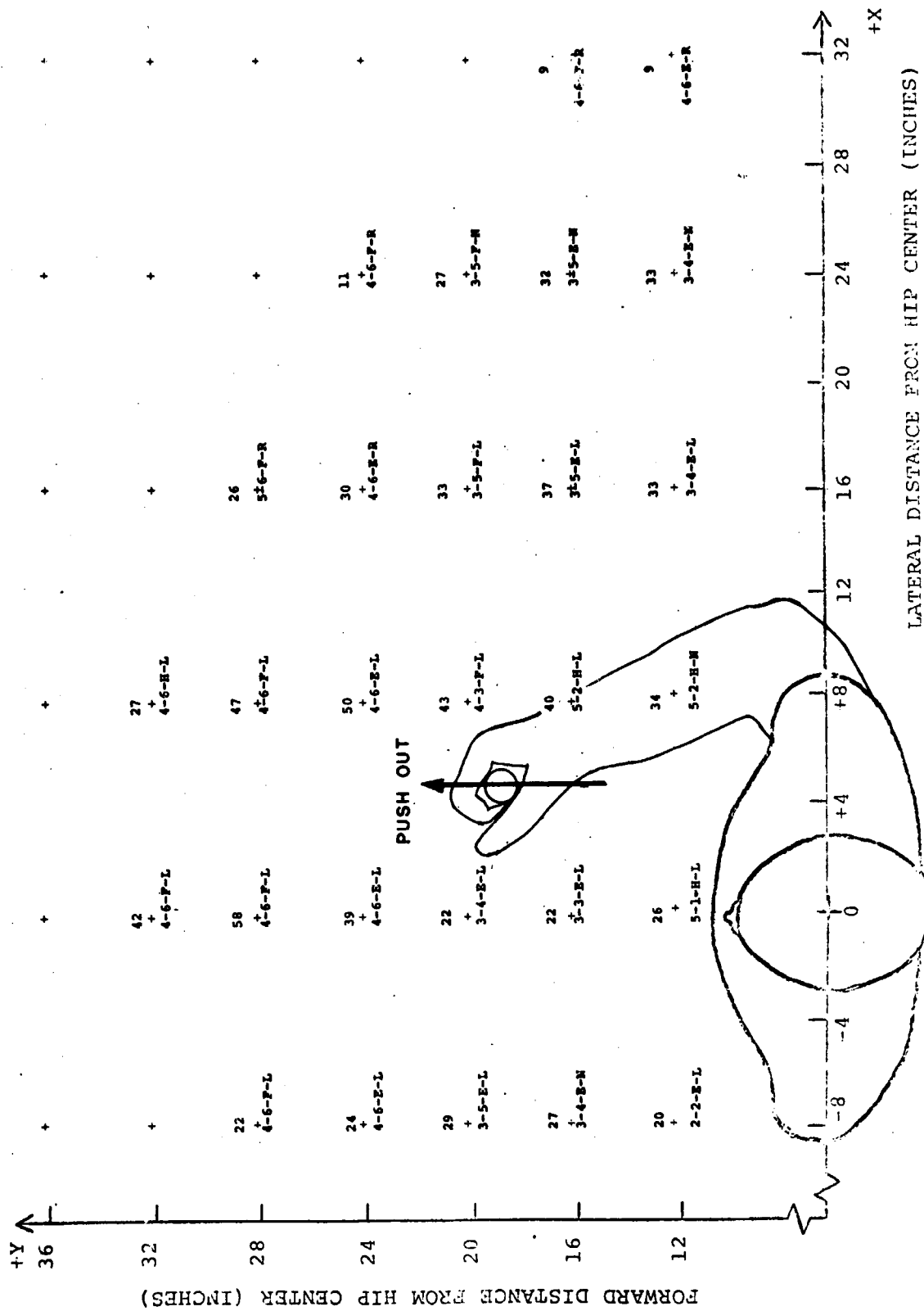


TABLE 31 Pushing-Out with Hand at 20 Inches above Hips (95% Man)

TABLE 32 Pushing-Out with Hand at 30 Inches above Hips (95% Man)

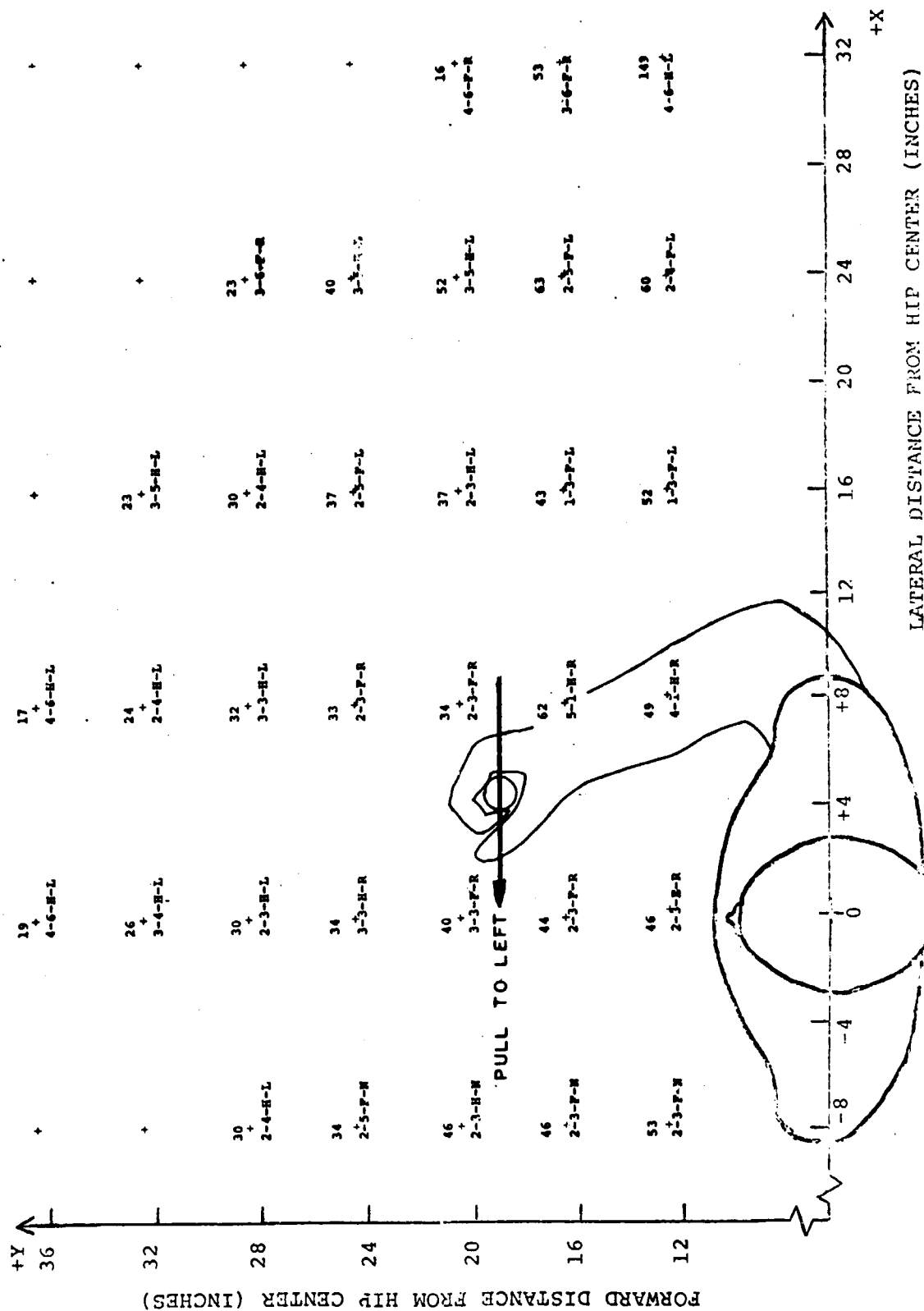


TABLE 33 Pulling -Across (right-to-left) with Hand 10 inches above Hips (95% Man)

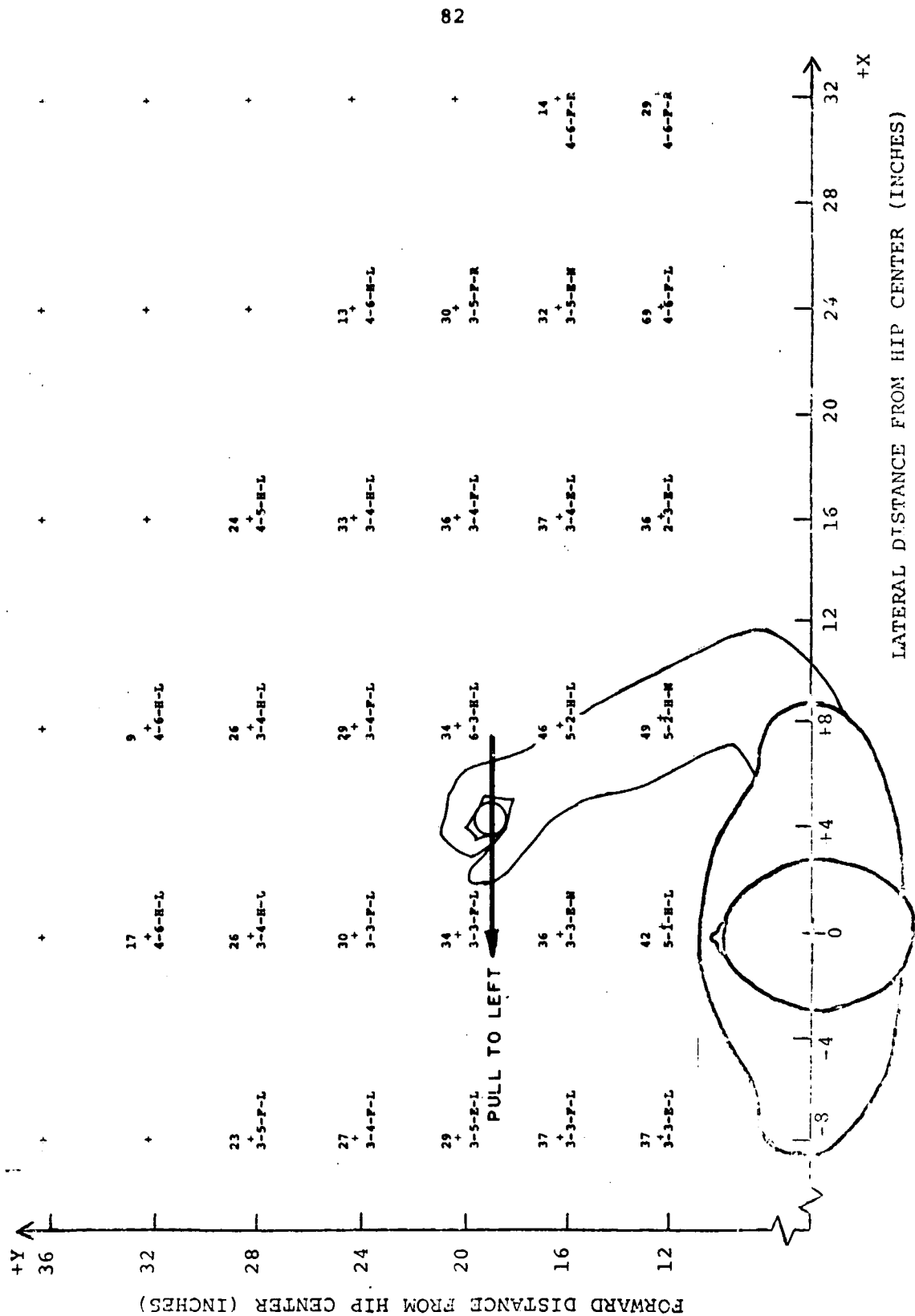


TABLE 34 Pulling-Across (right-to-left) with Hand 20 Inches Above Hips (95% Man)

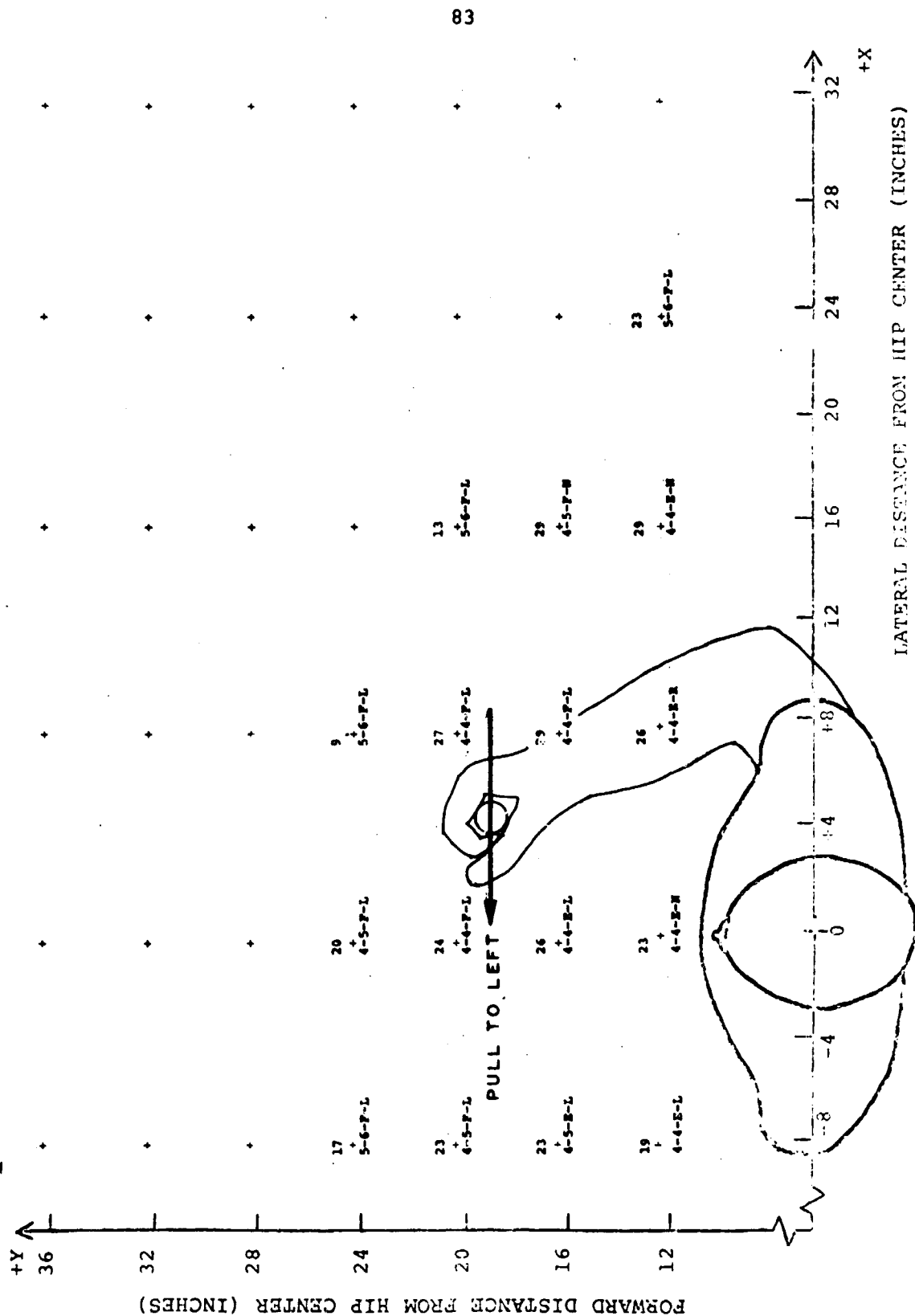


TABLE 35 Pulling-Across (right-to-left) with Hand 30 Inches above Hips (95% Man)

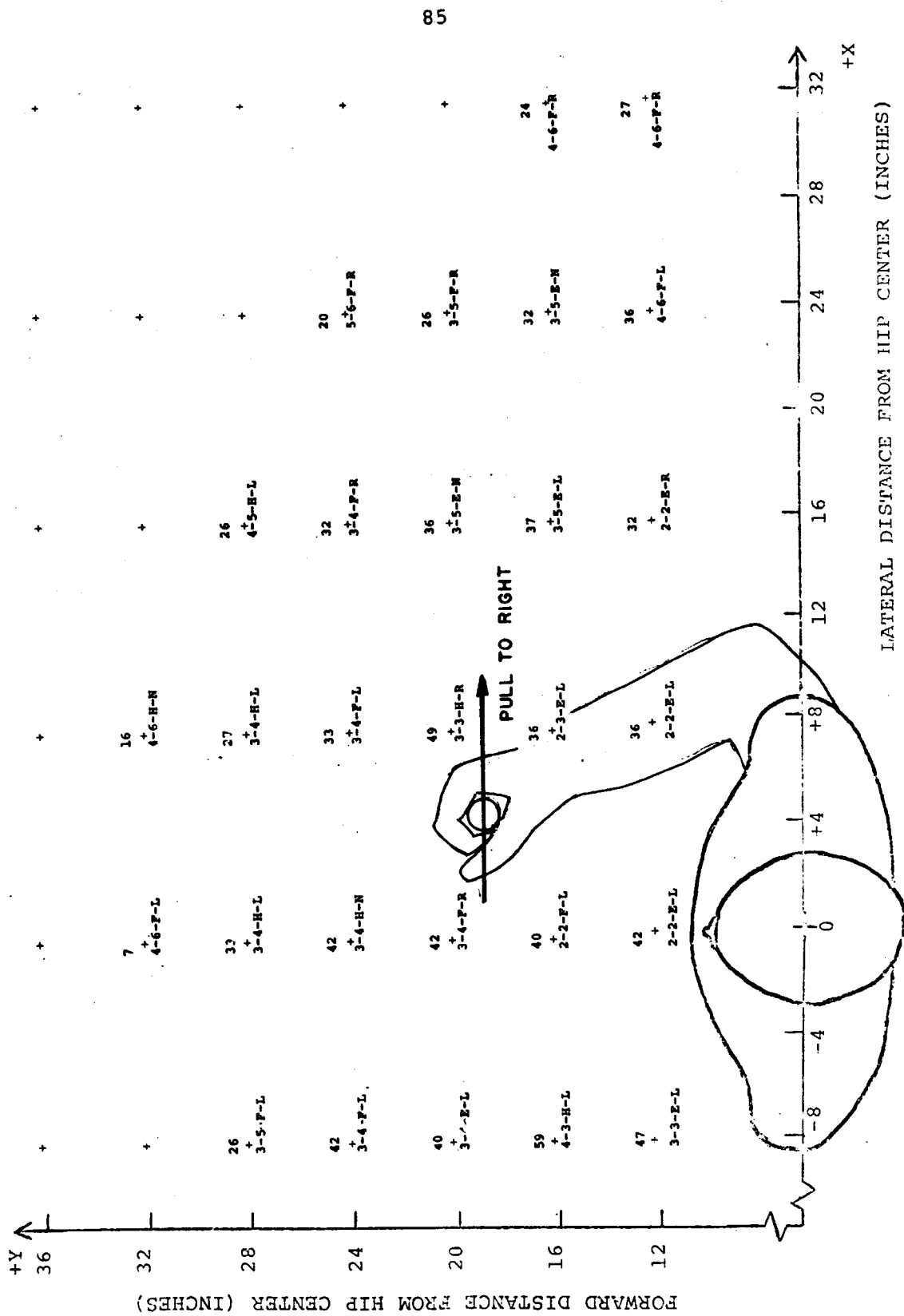
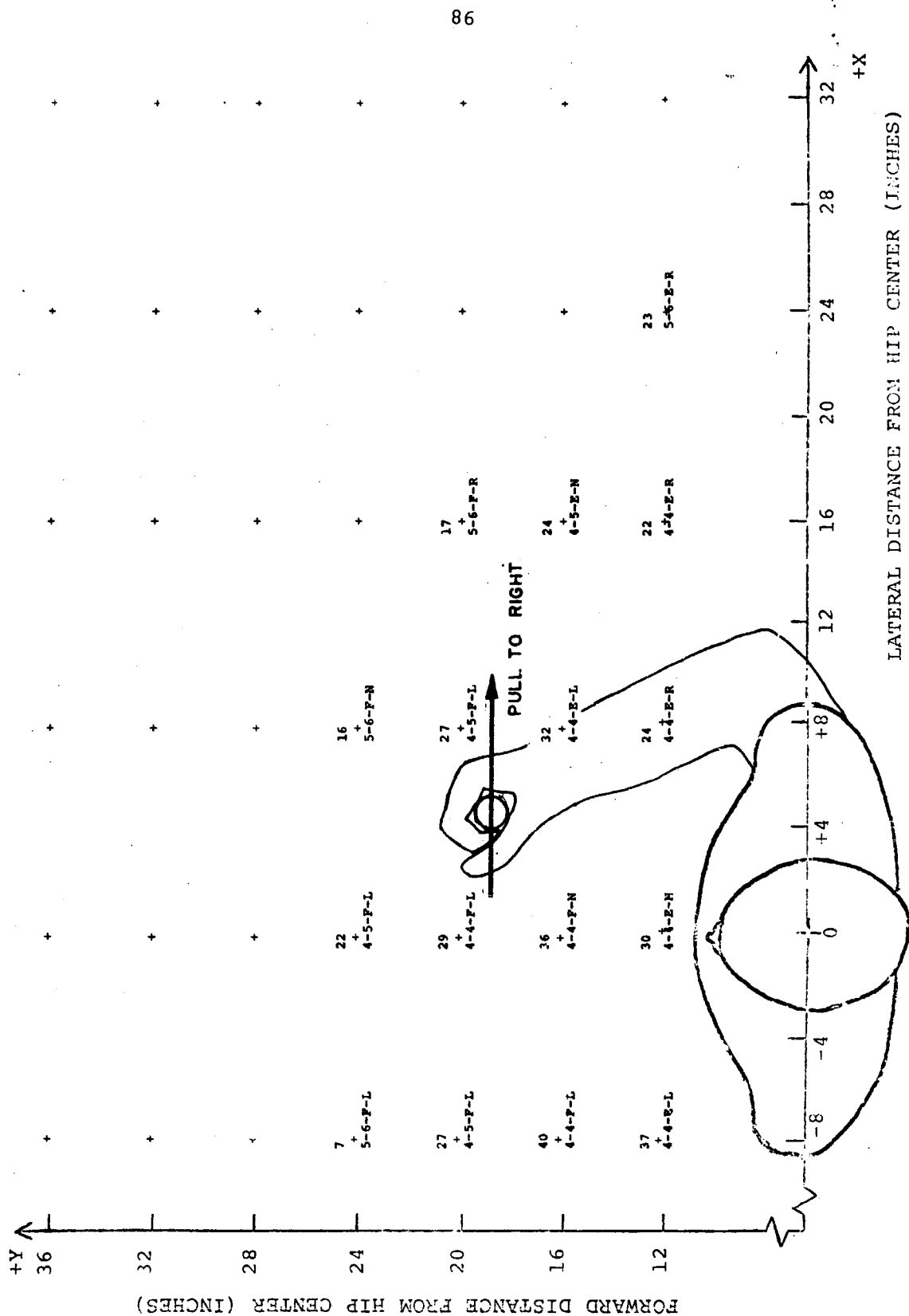


TABLE 37 Pulling-Across (left-to-right) with Hand 20 Inches Above Hips (95% Man)



Some General Observations Regarding Right Arm Strengths

Though hand position and force direction alone do not explain all of the variance in human strengths, they are major factors, as also concluded by Thordsen, et al. (1972), along with the manner in which a person is restrained and configures his body during an exertion. Because of the interdependencies of these and other factors, it is difficult to generalize regarding human strength behavior for any one factor. Yet some consistencies are present in the data and these are presented in the hopes that they will assist in understanding the data:

1. The small/weak (95% male) is capable of only about 50% of the average (50% male) strengths with the greatest differences in the lifting and pulling-down tasks and a lesser difference in the push, pull-in, pull-right, and pull-left tasks.
2. Larger hand forces are predicted when controls are placed in certain approximate regions within the simulated conditions, and depending upon the force directions required as follows (the smaller person can be seen to have a reduced region of maximal strength):
 - A. Lifting-up; from 12 to 26 inches on a radius from the hip center.
 - B. Pulling-down; from close-to-body to 28 inches on a radius from the hip

center, (this force is not greatly sensitive to hand position).

- C. Pulling-in; in front of the body at a distance of 24 inches to 32 inches.
- D. Pushing-out; in front of the body at a distance of 20 to 36 inches (or to maximum reach).
- E. Pulling-across (right-to-left); either to left or far right of body, and not beyond 20 inches in front of body.
- F. Pulling-across (left-to-right); either to right or far left of body, and not beyond 20 inches in front of body.

3. In general, the limiting muscle strengths were found to be the shoulder or elbow strengths, thus leading to a tentative hypothesis that similar two-handed seated strengths could be estimated by adding the right-hand values in the tables to the values found by assuming mirror-image locations for the left hand (corrected by 91% for the dominance factor discussed earlier).

From inspection of the tables it is obvious that generalization, such as above, are extremely gross approximations

of human strengths. It is therefore recommended that the user of these predictions not only consult the table values directly, but also refer to data from such other investigators as Hunsicker (1955, 1957), Watt (1963), and Thordsen, et al. (1972). By such comparisons good estimates of the effects of different population and task related variables can be ascertained.

V. Summary

The usual recommendation given in the past to a person who is concerned with specific strength factors is that the factors are extremely complex, and that little extrapolation or interpolation of existing studies can be made. Thus the person must set up his own experiments, often on an ad hoc basis. It is true that human strength is dependent upon many personnel and task related factors. Yet it is the contention of these investigators that many of the more important biomechanical factors affecting strength have been well enough studied that much of the so-called "unknown variation" reported by various researchers can be predicted. This does not mean that simple relationships exist, but that their complexity is amenable to present computational techniques via digital computers.

This project is an attempt to demonstrate the advancements in both the understanding and usefulness of existing human strength data that can be gained by modelling the data in a more comprehensive manner. It is not an attempt to explain why various researchers data differ based on biomechanical considerations, though this should be done. Rather it is an attempt to, (1) present in a concise manner a biomechanical strength model which is the culmination of over six years of investigation by over a dozen University of Michigan researchers, and (2) simulate a representative set of zero gravity exertions to enable a user to begin to

appreciate and anticipate some of the effects of the various strength determining factors.

It is hoped that the present approach will benefit future researchers by providing a logically produced set of strength predictions which can be compared to their own strength data. Any discrepancies found (and a number are expected) will then provide additional knowledge. In other words, it is firmly believed that human strength is a predictable phenomenon, and therefore its study is amenable to modelling. It should be noted, however, that the modelling will not be simply statistical in nature, but will need to rely on knowledge of the basic biomechanical, physiological, and psychological factors that are known to affect strength. The present model is a step down this much needed path of inquiry which undoubtedly will eventually lead to a larger understanding and thereby a more comprehensive prediction of human strengths.

From the practical standpoint the present model is useful for initial design evaluations, in that it can be implemented on any reasonable large digital computer that has a Fortran IV Compiler. Also, its input/output format allows control from remote teletype terminals, thus providing a design engineer with a convenient tool.

The results of the present strength simulations are not absolutely correct (as mentioned earlier its output correlates with actual exertions with a correlation coefficient of $r=.83$). This is believed to be sufficient,

however, to allow it to be used for the evaluation of many different design alternatives (both in hardware and procedures), prior to committing large sums of money and time on hardware mockups and empirical tests. Once some of the initially gross alternatives have been evaluated by the computerized simulation, then better mockups can be developed to refine the final designs and procedures.

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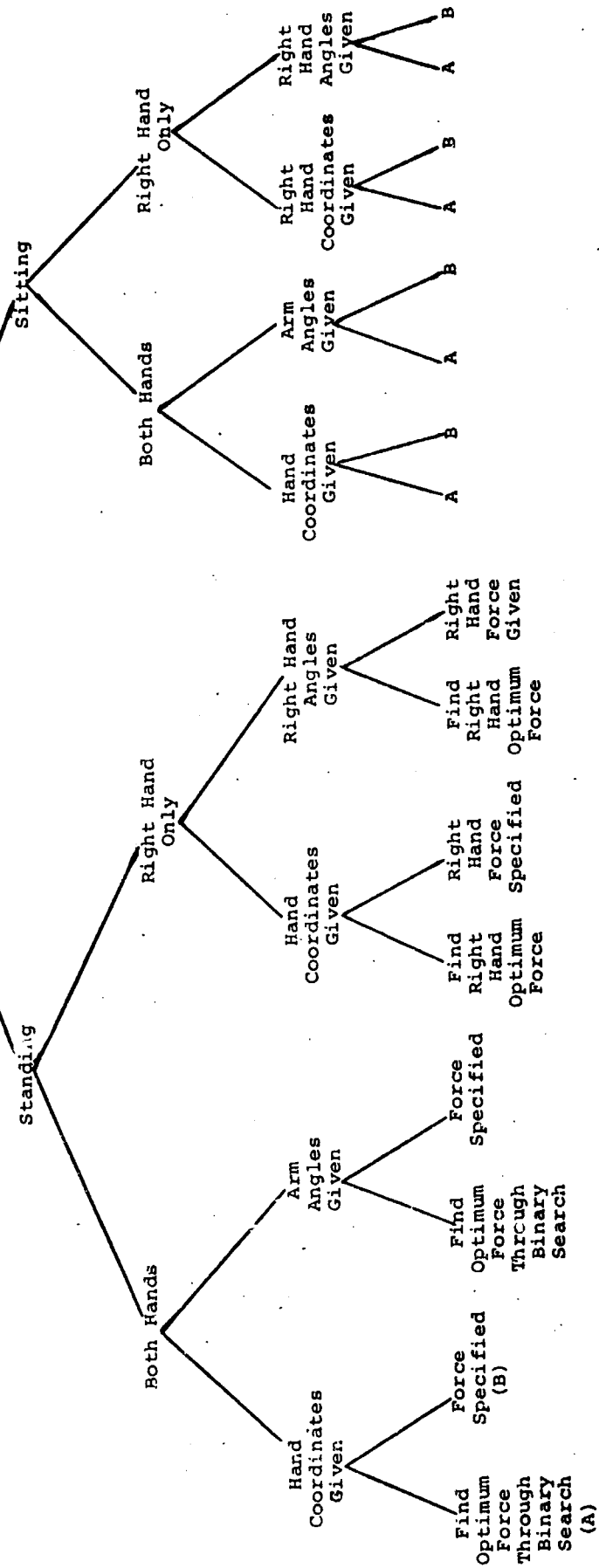
Appendix A

Input Data Format

and

Program Control Statements

DIFFERENT MODES IN WHICH PROGRAM CAN OPERATE



INPUT CARD FORMATS

For the Program

Biomechanical Analysis of Three Dimensional Strength

Human Performance Group

Department of Industrial Engineering

University of Michigan

NOTE: Everything should be right justified

Card #1

Sex of the subject and position (215)

Sex: Female = 1, Male = 2;

Position: Sitting = 1, Standing = 2;

1	2	3	4	5	6	7	8	9	10
					Sex				
					Position				

Card #2

Subject Dimensional Data (7F10.2)

Weight (lbs)	Height (inch)	Length of Foot (inch)
1	10	18
2	11	19
3	12	20
4	13	21
5	14	22
6	15	23
7	16	24
8	17	25
9	18	26
10	19	27
11	20	28
12	21	29
13	22	30
14	23	
15	24	
16	25	
17	26	
18	27	
19	28	
20	29	
21	30	
22		
23		
24		
25		
26		
27		
28		
29		
30		

Length of Tibia (inch)	Wrist to C.G. of Hand (inch)	Length of Radius (inch)
31		
32		
33		
34		
35		
36		
37		
38		
39		
40		
41		
42		
43		
44		
45		
46		
47		
48		
49		
50		
51		
52		
53		
54		
55		
56		
57		
58		
59		
60		

61 62 63 64 65 66 67 68 69 70
Elbow Height (inch)

Card #3

Subject Test Torque Data (5F10.2)
For Lower Torso.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
											Knee Extension (in-lbs)										Knee Flexion (in-lbs)									
	Ankle Extension (in-lbs)																													

[illegible]

Card 4 & 5

Subject Coefficients for Strength Equations to Give Maximum Voluntary
Torques for Upper Torso and Arms.

Card #4 (10F6.4)

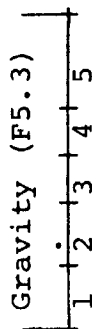
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Elbow Flexion						Elbow Extension						Horizontal Shoulder Backward						Horizontal Shoulder Forward						Vertical Shoulder Abduction					
31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Vertical Shoulder Adduction						Humeral Rotation Lateral						Humeral Rotation Medial						Trunk Rotation Right						Trunk Rotation Left					
																		(counterclockwise torque)						(clockwise torque)					

100

Card #5

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Trunk Flexion At L5-S1						Trunk Extension at L5-S1						Trunk Bending to The Left						Trunk Bending to The Right						Left Arm Strength					

Card #6



Card #7

Different Flags to be set to Determine Mode of Running (5I5)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
ISERCH					ICON					IFLAG2					IHAND					IFLAG3				

ISERCH (binary search)

ISERCH=1, No Binary Search Required i.e., No Search for Optimum Force

ISERCH=2, Binary Search Required

ICON (configuration of the arms)

ICON=1, Arm Angles are to be supplied as input

ICON=2, Hand coordinates are to be given as input.

IFLAG2

If IFLAG2=1, Legs and lower torso angles are such that maximum angle=minimum angle and therefore only one angle is to be read in for each joint.

If IFLAG2=1, Leg and lower torso angles will be read in the form, maximum, Increment, Minimum(for each joint)

IHAND (Right Hand or both hands)

IHAND=1, Binary Search will be done only on the right hand if ISERCH=2. Left Hand force will be specified.

IHAND=2, Binary Search will be done both on right as well as left hand forces.

Card #7 (cont'd)

IFLAG3 (Body Balance)

IFLAG3=1, No check for body balance will be made.

IFLAG3=0 (zero), Forward and backward balance will be checked.

Card #8

Forearm Rotation (2F10.2)

[illegible]

Card #9

Left hand force magnitude (F10.2)

To be read only if binary search is to be done only on right hand i.e. ISERCH=2, IHAND=1 in Card #7

1 2 3 4 5 6 7 8 9 10
Left Hand Force Magnitude

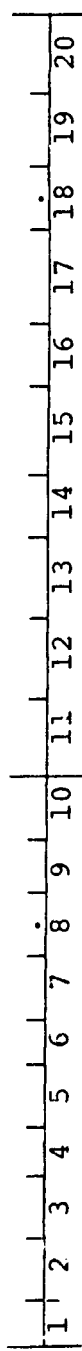
Card #10

Right hand and left hand force magnitude (2F10.2)

To be read only if no binary search is desired, i.e., `ISERCH=1`; in Card #7

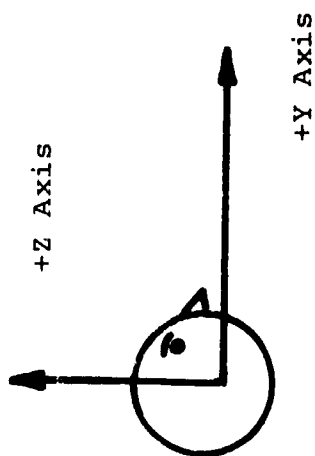
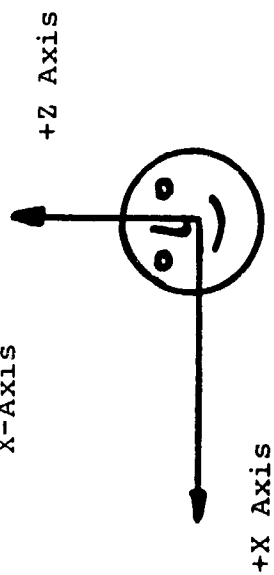
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Right Hand Force										Left Hand Force										
Magnitude										Magnitude										.

Right hand force direction (2F10.2)

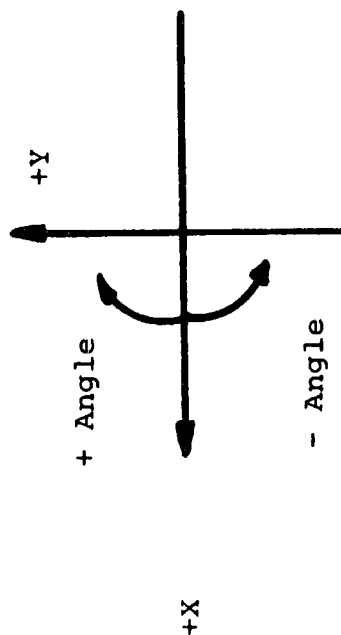


Force Angle From the
X-Axis

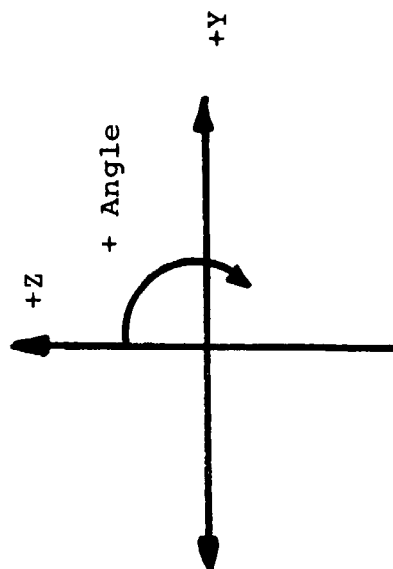
Force Angle From the
Z-Axis



X-Y is the horizontal plane



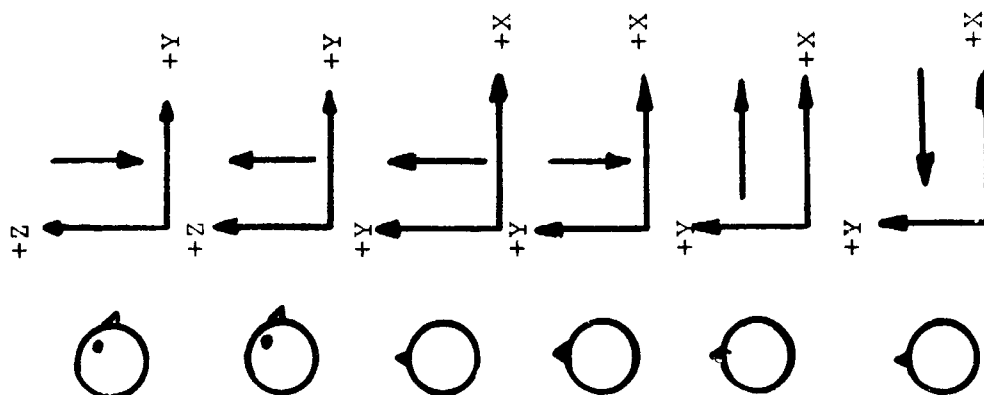
Angle from X-Axis



Angle From Z-Axis

Card #11 (cont'd)

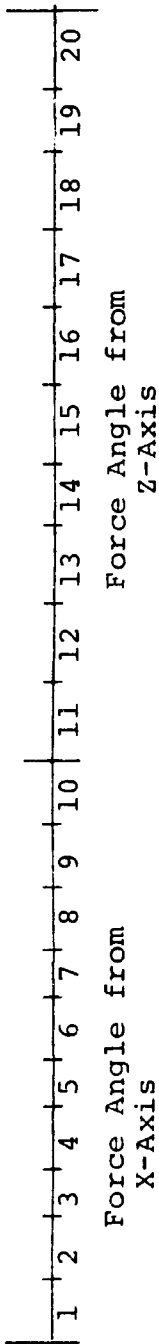
Examples:



Force Direction	Angle from X-Axis	Angle from Z-Axis
Lift	0.	180.
Push Down	0.	0.
Pull Towards the body	90.	90.
Push Away From the Body	-90.	90.
Pull Across to the Left	0.	90.
Pull Across to the Right	180.	90.

Card #12

Left hand force direction (2 Flo.2)



Same notation as in Card #11

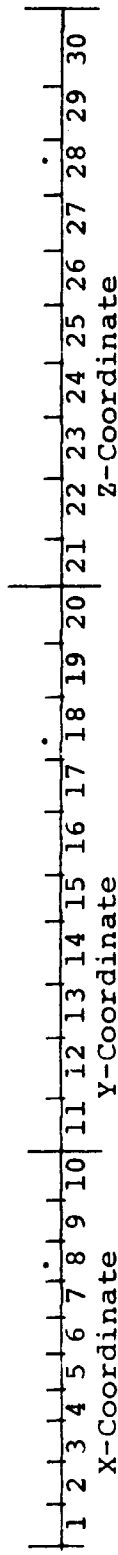
Card #13 & 14

Right hand and left hand coordinates to be read in only if the arm angles are not to be given in input. i.e. ICON=2 in Card #7

Note: origin is the ball of the right foot when position=standing
origin is bisection of the hip joints when position=sitting

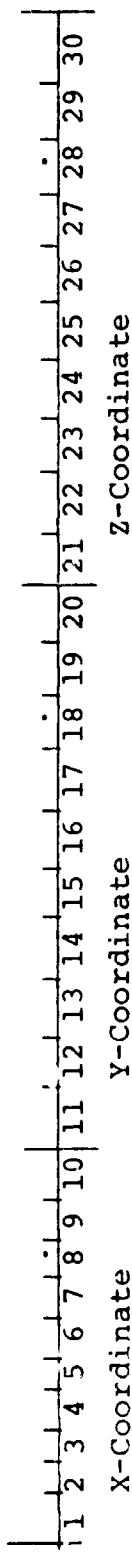
Card #13

Right hand coordinates (3 Flo.2)



Card #14

Left hand coordinates (3 Flo.2)



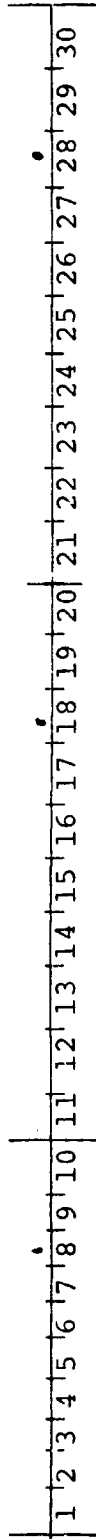
Card #15 & 16

Right hand and Left hand arm angles.

To be read in only if hand coordinates are not given. i.e. ICON=1 in Card #7

Card #15

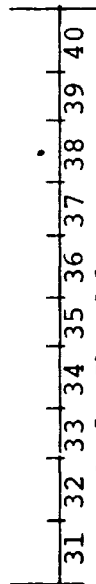
Shoulder vertical and horizontal angles (4 F10.2)



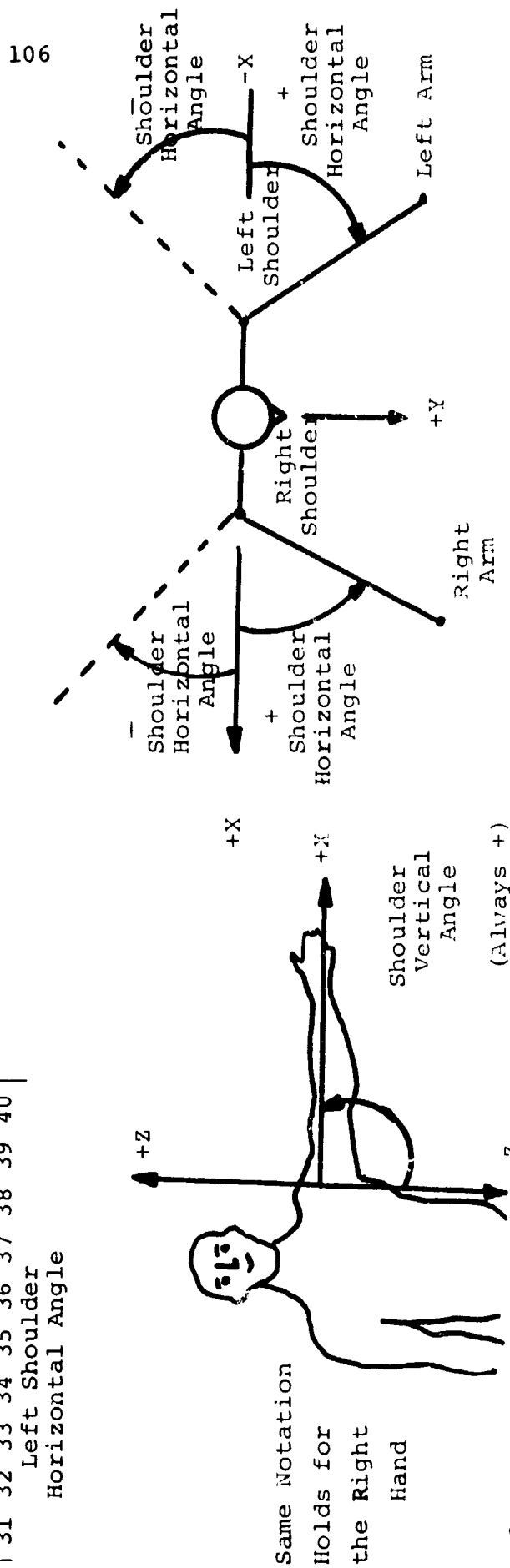
Right Shoulder
Vertical Angle

Left Shoulder
Vertical Angle

Right Shoulder
Horizontal Angle



Left Shoulder
Horizontal Angle



Same Notation
Holds for
the Right
Hand

Card #15 (cont'd)

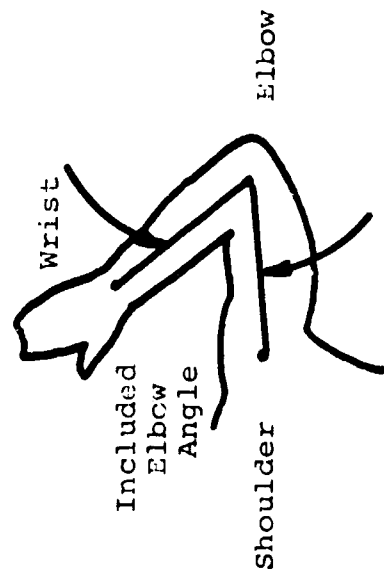
Shoulder Vertical Angle : Angle from Z-Axis in X-Z plane
 Shoulder Horizontal Angle : Angle from (+X) Axis in X-Y plane for right and left hands respectively
 Positive towards Positive Y.

Card #16

Humeral rotations and elbow angles. (4 Flo.2)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Right Hand										Left Hand										Right Hand									
Humeral Rotation										Humeral Rotation										Right Hand Included Elbow Angle									

31	32	33	34	35	36	37	38	39	40
Left Hand Included Elbow Angle									



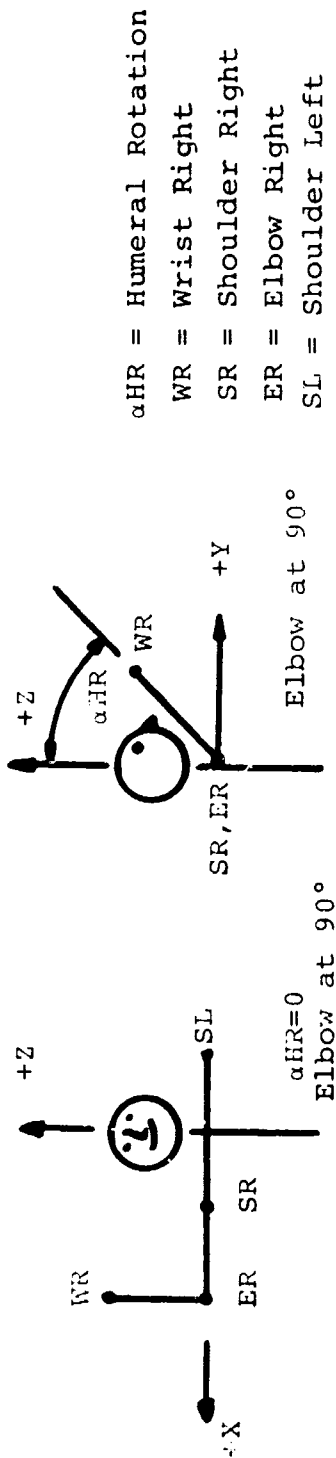
Limits
 Minimum Elbow Angle = 30°
 Maximum Elbow Angle = 180°

Card # 16 (cont'd)

Humeral Rotation - If elbow is considered as a pin joint, Humeral Rotation = 0. Now if forearm is rotated about the upper arm, rotation = humeral rotation angle, positive if rotation counterclockwise for right hand and clockwise for left hand.

or

it is that angle between wrist, elbow and shoulder plane (when upper arm is rotated such that it lies in X-Z plane) and the plane with 0° humeral rotation (i.e. plane formed by shoulder, elbow and wrist is the same as X-Z plane).



The following three cards are to be read in, only if IFLAG2=2 in Card #7

Card #17

Subject hip angle range and increment value. Angles are measured from positive Y-axis in Y-Z plane. Counter clockwise=positive.

HIPMAX = Largest hip angle to be evaluated. This value must be $< 110^\circ$.

HIPINC = The desired increment value between HIPMAX and HIPMIN. (A positive number)

HIPMIN = Smallest hip angle to be evaluated. This value must be $> -45^\circ$.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
HIPMAX										HIPINC										HIPMIN									
(max. hip angle)										(increment)										(min. hip angle)									

Card #18

Trunk Rotation angles and increment value (3 F10.2)
Trunk rotation angle is the rotation of the trunk at L5-S1 disk.
Positive counterclockwise (i.e. towards left)

TRRMAX =	Maximum	trunk	rotation angle	to be evaluated.	< 100
TRRMIN =	Minimum	trunk	rotation angle	to be evaluated.	> -100

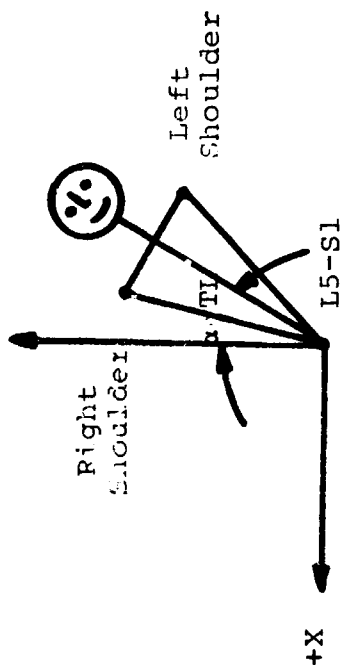
TRRINC = The desired increment value between TRRMAX and TRRMIN. (A positive number)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30																				
										TRRMAX																				TRRINC										TRRMIN									

Card # 19

Trunk lateral bending angles and increment value (3 Fl0.2)

That angle by which the trunk is laterally bent away from the vertical. A positive [negative] angle indicates that subject is laterally bent towards his right [left].

 α_{TL} = trunk lateral bending angle

TRBMAX - Maximum trunk lateral bending angle to be evaluated < 45

TRBMIN - Minimum trunk lateral bending angle to be evaluated > -45

TRBINC - The desired increment value between TRBMAX and TRBMIN. A positive number.

[illegible]

Hip angle, trunk rotation and trunk bending angles. To be read in only if maximum = minimum for all the three angles and IFLAG2 = 1 in Card #7. They are defined in the same manner as in Cards # 17, 18, and 19.

The following cards are to be read in only if Position = Standing (see Card #1). Moreover, the following 6 cards are to be read in, only if IFLAG2 (in Card #7) = 2, if IFLAG2= 1, then the following 6 cards are to be skipped and only the last card is to be read in.

Foot distance=between the ball of the right foot and the ball of the left foot when the left foot is behind the right foot. (3 F10.2)

BFTMAX = Maximum backward foot distance to be evaluated. (A positive number)
BFTINC = The desired increment value between maximum and minimum backward foot distance (A positive number)

BFTMIN = Minimum backward foot distance to be evaluated. (A positive number) > 0

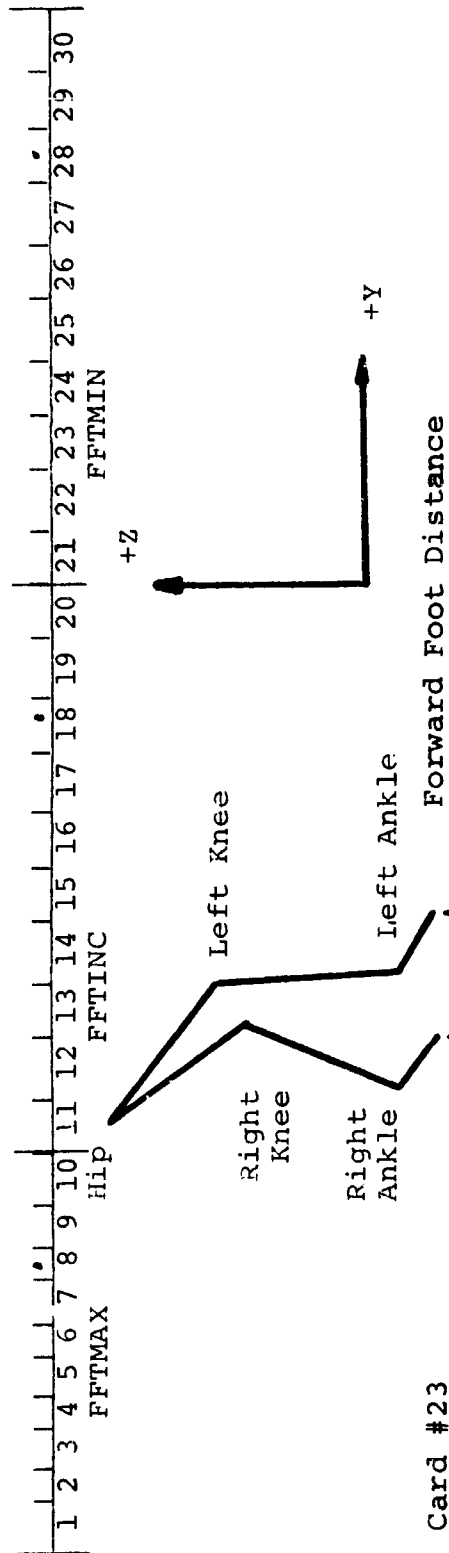
Card #22

Foot distance. Same as Card #21, except now right foot is behind left foot. (3 F10.2)

FFTMAX = Maximum forward foot distance to be evaluated. A positive number.

FFTINC = The desired increment value between minimum and maximum forward foot distance. A positive number.

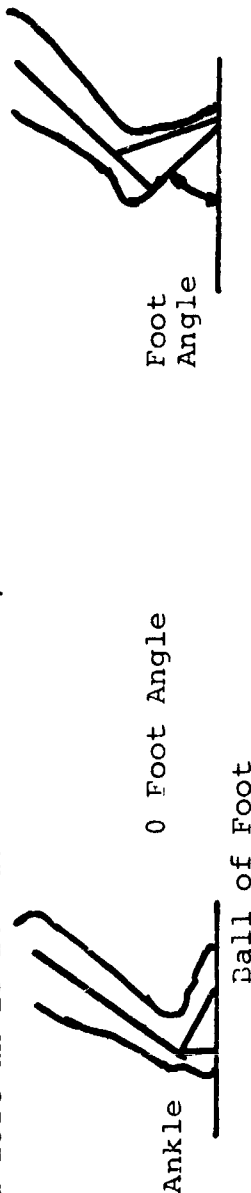
FTMIN = Minimum forward foot distance to be evaluated. A positive number.



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Card #23

Backward foot angle = Angle by which the vector joining the ball of left foot and left ankle is turned clockwise, when left foot is behind the right foot. (3 F10.2)



BFAMAX = Maximum backward foot angle to be evaluated. A positive number.

BFAINC = Increment values between minimum and maximum backward foot angles. A positive number.

BFAMIN = Minimum backward foot angle to be evaluated. A positive number.

[illegible]

Forward foot angle = same as backward foot angle (Card #23), except right ankle and right ball of foot instead of left ankle and left ball of foot.

FFAMAX = Maximum forward foot angle to be evaluated. A positive number.

FFAMIN = Minimum forward foot angle to be evaluated. A positive number..

Subject ankle angle range and increment values (degrees) (3F10.2).
Angles are measured from Positive Y-Axis in Y-Z plane. Counterclockwise. positive.

ANKMAX = Largest ankle angle for the right leg to be evaluated. A positive number. < 110.

ANKMIN = Smallest ankle angle for the right leg to be evaluated. A Positive number.

Card #25 (cont'd)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Card #26

Subject knee angle and increment value. (3 F10.2)
Angles are measured from positive Y-Axis in Y-Z plane. Counter clockwise positive.

Note: Knee angle is read in only for right leg. Knee angle for the left leg is calculated by subroutine LBODY.

KNEMAX - Maximum knee angle to be evaluated. A Positive number. < 220

KNEINC - The desired increment value between minimum and maximum knee angle = a positive number

KNEMIN - Minimum knee angle to be evaluated. A positive number. > Max {50°, ANKMIN}

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
---	---	---	---	---	---	---	---	---	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----

Card #27

This card is to be read in only if the Cards #21 to 26 are not read. i.e. IFLAG2=1 in Card #7. This card is read in when minimum angle = maximum angle and no increments are desired at any of body link joints. (6 F10.2)

The variables are defined in the same manner as in Card #21 to #26.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

BFTMAX FFTMAX BFTMAX

[illegible]

Card #27 (cont'd)

Note: When this card is read in, minimum is set to maximum and increment = 0, for each angle.

Note: If more than one data sets are to be read in for the same subject with the same flags (Card #7) on, to continue the next data set go back to Card #8. This will save you loading time.

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Appendix B

*Output Data Example

*Description of Various Logic Used in Model

Detailed flow charts and variable listing are available as an Addendum from the following:

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OUTPUT

Following points are to be noted in interpreting the output, (an example output is presented later in Appendix).

A. 'NO FEASIBLE POSITION POSSIBLE FOR HANDS'

This line is printed out if after simulating all body positions possible, a feasible position for arms (either left or right or both) cannot be found which will place the hands at the desired coordinates within the constraints of the model. In this case a slightly different set of coordinates might be tried.

B. PLOT

This prints

1. The coordinates of the various joints
2. The force directions on hands, both in front as well as right-hand side view.

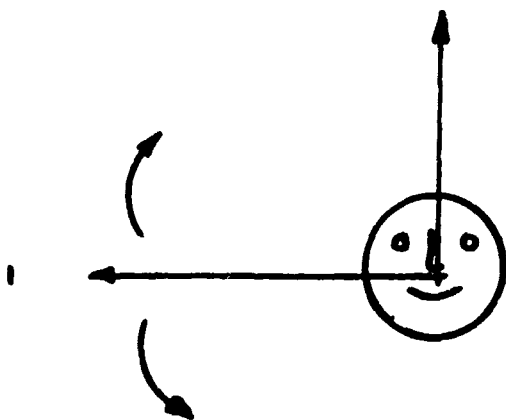
The numerals (1,2,...,9,0) represent right hand side of the body while the letters represent left hand side of the body.

To get the stick figure out of these numbers and letters, the following interpretation is to be used:

1, B	Ball of foot
2, A	Ankle
3, K	Knee
4, P	Hip
5	L5-S1 disk
6, S	Shoulder
7, E	Elbow
8, H	C.G. of hand
9	Midpoint of the line joining the shoulder. Corresponds to neck.
0	Head.

- C. Program prints only the optimum body position (corresponding to maximum force) for a given set of input.
- D. Most of the output is self explanatory. Notations followed for hand coordinates, force direction, arm and body angles are the same as explained in input except for the 'shoulder vertical angle'.

Here the shoulder vertical angle is = shoulder vertical angle of input $_ 90^\circ$



- E. Attached is an actual computer output for two-handed strength. First the program prints two labels saying to whom it belongs and the name of the programmer.

Then it prints subject position, i.e. either standing or sitting.

Next block is for subject's personal data, giving relevant information, i.e. sex, weights of various limbs, lengths of various limbs and subject's standard voluntary torques for the lower torso. Then gravity is printed.

The above information is printed only once for one computer run, as these attributes cannot be changed in one computer run.

Next printing is force directions and coordinates of right and left hands with their respective labels.

Then program prints the distance between left and right leg, saying whether left leg is behind the right leg or forward to it. After this, foot, ankle and knee angles are printed for left and right legs. Next printing is the trunk flexion, lateral bending and trunk rotation angles.

Following this, right and left shoulder or arm angles are printed. These angles comprise vertical arm angle, horizontal arm angle, humeral rotation and included elbow angle.

Next step is the force magnitudes on the right and left hands which the subject can exert without exceeding any strength limits on any joint in any direction, and it also prints the limiting muscle groups.

In the end, program prints the coordinates of the various joints and force direction in two views, namely

1. front view
2. right-hand side view

CONTROL FOR THE OUTPUT

Input is read in through Channel 5. There are two channels for output, namely 6 and 7. Channel 6 points the output shown in the attached sample output. Channel 7 gives the X, Y and Z coordinates of all the body joints for the body position corresponding to this output. The reference point for the output is the ball of the right foot in both the cases, i.e. the subject is standing or sitting.

If this output is not desired, Channel 7 can be connected to a temporary or dummy file in the control card.

Example Computer Output

```
*****
*
* PROGRAM FOR BIOMECHANICAL ANALYSIS OF THREE DIMENSIONAL STRENGTH *
*
* HUMAN PERFORMANCE GROUP *
*
* DEPARTMENT OF INDUSTRIAL ENGINEERING *
*
* UNIVERSITY OF MICHIGAN *
*
*****
```

```
*****
*
* PROGRAMMED BY ARUN GARG *
*
*****
```

```
*****
*
* STANDING POSITION *
*
*****
```

```
*****
*
* THE FOLLOWING DATA CHARACTERISTICS APPLY TO THIS SUBJECT: *
*
* SEX = MALE *
* WEIGHT = 167.2 LB. *
* HEIGHT = 70.0 IN. *
* LENGTH, RADIUS = 10.2 IN. *
* LENGTH, WRIST TO CG OF HAND = 3.8 IN. *
* LENGTH, TIBIA = 16.5 IN. *
* LENGTH, FOOT = 10.0 IN. *
* ELBOW HEIGHT = 44.5 IN. *
* TEST TORQUE OF ANKLE, EXTENSION = 1969.8 IN.-LB. *
* TEST TORQUE OF KNEE, EXTENSION = 1614.3 IN.-LB. *
* TEST TORQUE OF KNEE, FLEXION = 455.7 IN.-LB. *
* TEST TORQUE OF HIP, EXTENSION = 2988.0 IN.-LB. *
* TEST TORQUE OF HIP, FLEXION = 1358.0 IN.-LB. *
```

GRAVITY=0.0

PRECEDING PAGE BLANK NOT FILMED

	* FORCE DIRECTION	
	HORIZONTAL ANGLE FROM X-AXIS	VERTICAL ANGLE FROM Z-AXIS
RIGHT HAND	0.0	180.00
LEFT HAND	0.0	180.00
	RIGHT HAND COORDINATES	LEFT HAND COORDINATES
X	6.00	-17.00
Y	4.00	4.00
Z	80.00	80.00

LEFT FOOT IS 12.0 INCH BACKWARD FROM RIGHT FOOT

RIGHT FOOT ANGLES			LEFT FOOT ANGLES		
FOOT	ANKLE	KNEE	FOOT	ANKLE	KNEE
0.0	90.0	100.0	20.0	64.0	91.2

TRUNK ANGLES ARE		
HIP	TRUNK BENDING	TRUNK ROTATION
80.0	0.0	0.0

RIGHT SHOULDER ANGLES			
VERTICAL	HORIZONTAL	HUMERAL ROTA	ELBOW
68.68	92.61	0.0	180.00

LEFT SHOULDER ANGLES			
VERTICAL	HORIZONTAL	HUMERAL ROTA	ELBOW
60.64	69.17	0.0	180.00

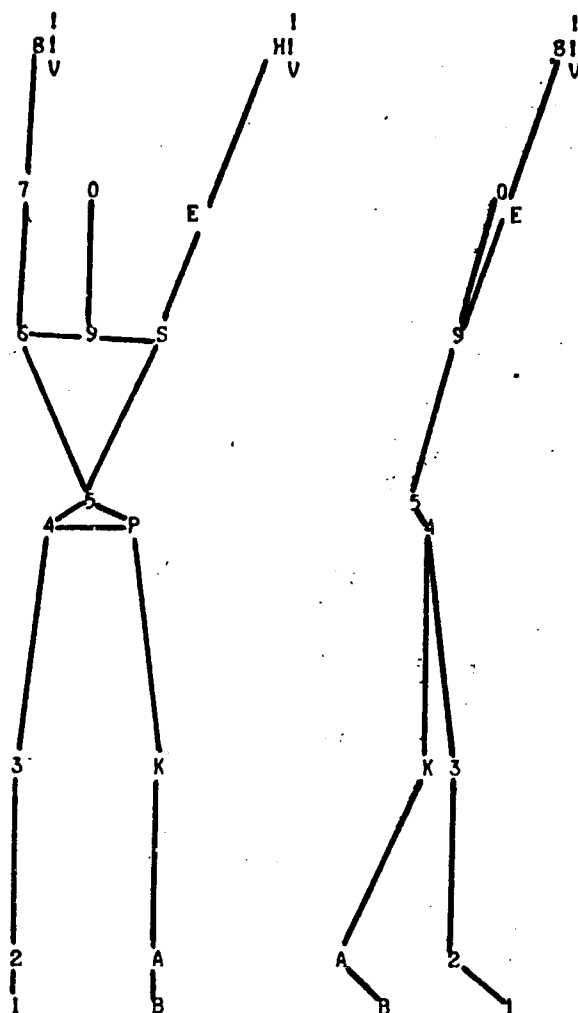
* RIGHT HAND FORCE
66.74

LEFT HAND FORCE
34.14

* LIMIT DUE TO

LEFT ELBOW EXTENSION

RIGHT SHOULDER VERTICAL ABDUCTION



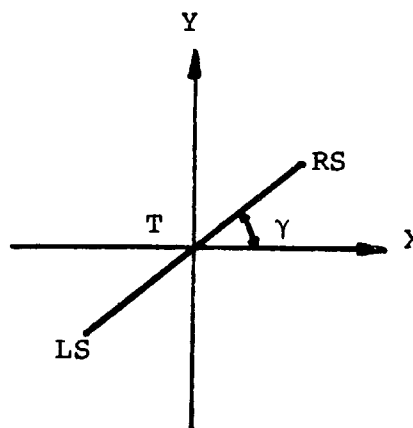
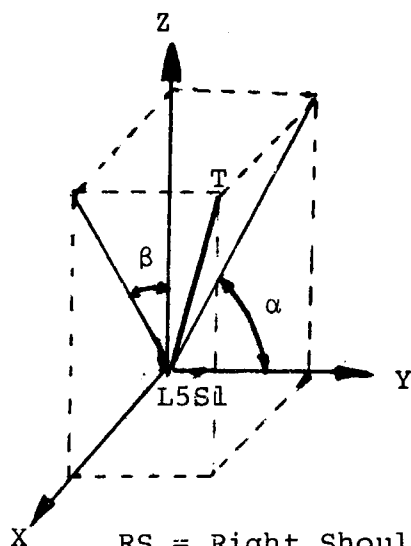
#SIG SAGU PW=
 ***LAST_SIGNON WAS: 17:08.05 04-22-72
 # USER "SAGU" SIGNED ON AT 16:54.15 ON 04-23-72
 #R OBJ 5=DATA6(1,7)+DATA6(50,63) 7=-A
 #EXECUTION BEGINS

Descriptions of Various Logic Used in Model

1. Determination of Right and Left Shoulder Coordinates

Left and right shoulder coordinates are a function of:

- A. Trunk flexion angle at L5-S1 disc. (α)
- B. Trunk lateral bending angle. (β)
- C. Trunk rotation. (γ)



RS = Right Shoulder

LS = Left Shoulder

T = Middle point of line joining right and left shoulder

a = Length from L5S1 to T

b = T to LS or RS

SL, XR, YL, YR, ZL and ZR are X, Y and Z coordinates of the left and right shoulders respectively.

Coordinates of right and left shoulders with respect to LS51 are given by the following equations:

$$XL = |a \cdot \sin(\alpha) \cdot \sin(\beta) - b \cdot \cos(\beta) \cdot \cos(\gamma)|$$

$$YL = a \cdot \cos(\alpha) - b \cdot \cos(\beta) \cdot \sin(\gamma)$$

$$ZL = a \cdot \sin(\alpha) \cdot \cos(\beta) + b \cdot \sin(\beta)$$

$$XR = |a \cdot \sin(\alpha) \cdot \sin(\beta) + b \cdot \cos(\beta) \cdot \cos(\gamma)|$$

$$YR = a \cdot \cos(\alpha) + b \cdot \cos(\beta) \cdot \sin(\gamma)$$

$$ZR = a \cdot \sin(\alpha) \cdot \cos(\beta) - b \cdot \sin(\beta)$$

2. Calculations for Right and Left Hand Coordinates:

Right and left hand coordinates are a function of:

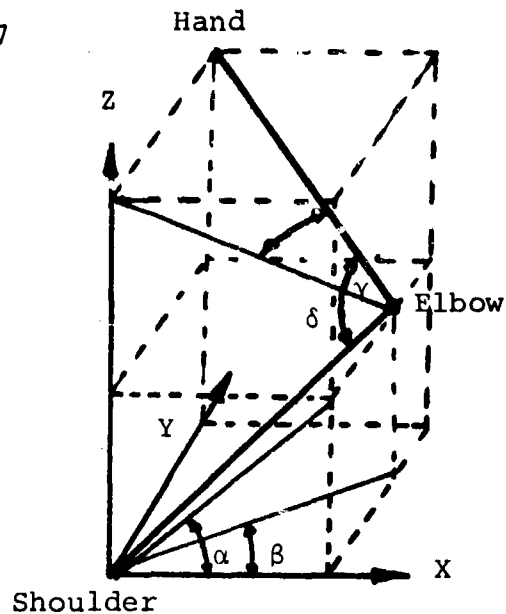
- A. Shoulder vertical abduction angle. (α)
- B. Horizontal shoulder flexion angle. (β)
- C. Humeral rotation angle. (γ)
- D. Included elbow angle. (δ)

These angles have been defined in the input section.

a = Shoulder to elbow distance.

b = Elbow to C.G. of hand

Let XL, XR, YL, YR, ZL, ZR be the X, Y and Z left and right hand coordinates. Then the left and right hand coordinates with respect to left and right shoulders are given by:



$$\begin{aligned}
 XL &= -(a-b*\cos(\gamma)*\cos(\delta))*\cos(\alpha)*\cos(\beta)+b*\sin(\gamma) \\
 &\quad * \sin(\beta)*\sin(\delta)+b*\sin(\delta)*\sin(\alpha)*\sin(\gamma)*\cos(\beta) \\
 XR &= (a-b*\cos(\gamma)*\cos(\delta))*\cos(\alpha)*\cos(\beta)-b*\sin(\gamma) \\
 &\quad * \sin(\beta)*\sin(\delta)-b*\sin(\delta)*\sin(\alpha)*\sin(\gamma)*\cos(\beta) \\
 YL &= (a-b*\cos(\gamma)*\cos(\delta))*\cos(\alpha)*\sin(\beta)+b*\sin(\gamma) \\
 &\quad * \cos(\beta)*\sin(\delta)-b*\sin(\delta)*\sin(\alpha)*\cos(\gamma)*\sin(\beta) \\
 YR &= (a-b*\cos(\gamma)*\cos(\delta))*\cos(\alpha)*\sin(\beta)+b*\sin(\gamma) \\
 &\quad * \cos(\beta)*\cos(\delta)-b*\sin(\delta)*\sin(\alpha)*\cos(\gamma)*\sin(\beta) \\
 ZL &= (a-b*\cos(\gamma)*\cos(\delta))*\sin(\alpha)+b*\cos(\gamma)*\sin(\delta)*\cos(\alpha) \\
 ZR &= (a-b*\cos(\gamma)*\cos(\delta))*\sin(\alpha)+b*\cos(\gamma)*\sin(\delta)*\cos(\alpha)
 \end{aligned}$$

In addition, if the included elbow angle is 180° (i.e. the arms are straight), then these equations do not hold. In this particular case, the following simple equations will give the desired coordinates:

$$\begin{aligned}
 XL &= -(a+b)*\cos(\alpha)*\cos(\beta) \\
 XR &= (a+b)*\cos(\alpha)*\cos(\beta) \\
 YL &= (a+b)*\cos(\alpha)*\sin(\beta) \\
 YR &= (a+b)*\cos(\alpha)*\sin(\beta)
 \end{aligned}$$

$$ZL = (a+b)*\sin(\alpha)$$

$$AR = (a+b)*\sin(\alpha)$$

3. Binary Search for Maximum Hand Forces:

A. Right Hand Only:

1. Perform the binary search on the right hand force, checking the limits on the right elbow and right shoulder.
2. Once the optimum right hand force is found, check whether it exceeds the following limits (a) the upper or lower torso strengths, the balance is lost (if desired), or leg strength is critical. If none of the limits is exceeded then the right hand force is optimum, otherwise a binary search is restarted starting with the preceding optimum torso and leg forces as the initial force, and is searched until the elbow and shoulder limits are not exceeded.

This makes efficient use of computer time because most of the time people are limited either by their elbows or shoulders strengths when the hands are located away from the torso.

B. Both Right and Left Hands:

1. Perform the binary search on the right hand force, checking the limits on elbow and shoulders only.

2. Perform the same check on the left hand force.
3. If these forces do not exceed any limits on the torso or legs (if standing), or low back, or body balance, then they are considered to be the optimum.

If they exceed any of the above limits, a binary search is performed on both the right and left hand forces simultaneously, by either decreasing or increasing them by half until the lower and upper limits at either the right hand or the left hand forces are within a difference of one pound of force.

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Appendix C

Procedure for Determining Strength Coefficients

The following steps were used in deriving the strength coefficients:

1. From sagittal plane strengths in Table II derive difference in population percentiles relative to 50% male strengths. These are:

Sagittal Plane Muscle Action:	95% vs. 50% Male	50% vs. 5% Male
Elbow Flexion	.708	1.333
Elbow Extension	.742	1.295
Shoulder Flexion	.696	1.346
Shoulder Extension	.706	1.336
Hip Flexion	.757	1.277
Hip Extension	.553	1.510
Shoulder Flexion & Shoulder Extension	.701	1.341
Hip Flexion & Hip Extension	.617	1.437

2. From muscle group prediction equation in Schanne, 1972, predict strength in positions from which above data was generated:

Elbow Flexion @ $\alpha_E = 90^\circ$: $T_E = 336.295 + 2.088\alpha_E - .015\alpha_E^2$

$$T_E = 403$$

Elbow Extension @ $\alpha_E = 90^\circ$: $T_E = 264.153 - .575\alpha_E$

$$T_E = 212$$

Shoulder Flexion (Vertical Shoulder Abduction)

@ $\alpha_E = 90^\circ$, $\alpha_{HS} = 90^\circ$, $\alpha_{VS} = 30^\circ$, $\alpha_{HR} = 0^\circ$: $T_S = 227.338 + .525\alpha_E -$

$$.372\alpha_{HR} - .296\alpha_{VS}$$

$$T_S = 266$$

Shoulder Extension (Vertical Shoulder Adduction)

$$@\alpha_{HS}=90^\circ, \alpha_{VS}=30^\circ: T_S=149.392-.161\alpha_{HS}+.0086\alpha_{HS}-$$

$$.099\alpha_{VS}$$

$$T_S=202$$

$$\text{Trunk Flexion } @\alpha_{TF}=90^\circ: T_{L5}=141.179+3.694\alpha_{TF}=47^A$$

$$\text{Trunk Extension } @\alpha_{TF}=90^\circ: T_{L5}=3365.123-23.947\alpha_{TF}=$$

$$=1210$$

3. Compute mean coefficient for males (subjects no.1-10) for each muscle group in Schanne's Thesis (1972).

These are:

Elbow Flexion: 1.66
 Elbow Extension: 1.86
 Horizontal Shoulder Rotation Back: 2.17
 Horizontal Shoulder Rotation Forward: 1.76
 Vertical Shoulder Abduction: 1.87
 Vertical Shoulder Adduction: 2.78
 Humeral Rotation-Lateral: 2.16
 Humeral Rotation-Medial: 1.26
 Trunk Rotation-Right: 1.72
 Trunk Rotation-Left: 2.30
 Trunk Flexion: 1.25
 Trunk Extension: 2.60
 Trunk Lateral Bending-Left: 2.16
 Trunk Lateral Bending-Right: 1.48

4. Multiply torques from Step 2 by coefficients from Step 3.
5. Divide torques in Table II by those from Step 4.
 [Note: for humeral rotation and horizontal shoulder strengths, use average of shoulder flexion and extension; for trunk rotation and lateral bend use average of hip flexion and extension strengths].
 This procedure then produces subject coefficients for 50% male:

Elbow Flexion = .922
 Elbow Extension = .961
 Vertical Shoulder Abduction = 1.494
 Vertical Shoulder Adduction = 1.331
 Humeral Rotation-Lateral = 3.041
 Humeral Rotation-Medial = 1.774
 Horizontal Shoulder Rotation-Back = 3.055
 Horizontal Shoulder Rotation-Forward = 2.478
 Trunk Flexion = 4.589
 Trunk Extension = 1.900
 Trunk Rotation-Right = 4.589
 Trunk Rotation-Left = 5.350
 Trunk Lateral Bend - Left = 5.024
 Trunk Lateral Bend - Right = 3.443

6. Finally, multiply coefficients in Step 5 by proportions in Step 1, thus yielding 95% and 5% subject coefficients, as follows:

Muscle Strength for Input- Appendix A	95% Weak	50% Average	5% Strong
EF	.653	.922	1.229
EE	.713	.961	1.244
VSABD	1.040	1.494	2.011
VSADD	.940	1.331	1.778
HSRF	1.743	2.478	3.335
HSRB	2.142	3.055	4.097
HRM	1.244	1.774	2.379
HRL	2.132	3.041	4.078
TF	3.474	4.589	5.860
TE	1.051	1.900	2.869
TRR	2.469	4.001	5.749
TRL	3.301	5.350	7.688
TBL	3.100	5.024	7.219
TBR	2.124	3.443	4.948

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Appendix D

A Strength Bibliography

compiled by
Frederick Schanne

January 1972

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