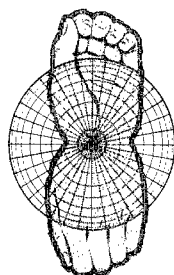


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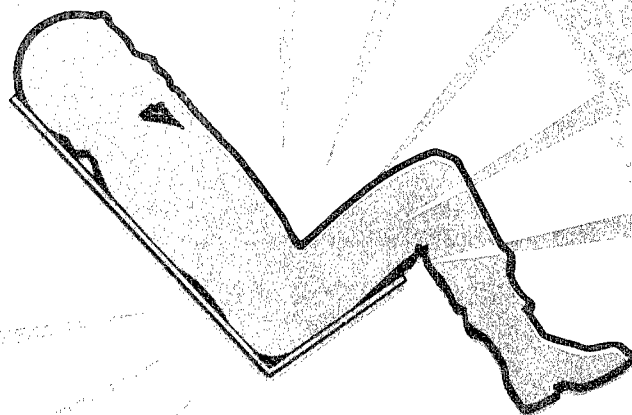
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ANTHROPOMETRY
LABORATORY



HUMAN
FACTORS

THE EFFECT OF ACCELERATION ON HUMAN CENTERS OF GRAVITY



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GENERAL DYNAMICS | FORT WORTH

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ABSTRACT

The location in two-dimensional (x-z) space of the center of gravity of the seated human body was studied on 25 living male subjects under conditions of experimentally controlled changes in the angle at which a one "g" acceleration acted upon the completely restrained body.

It was found that varying the direction of acceleration from 15° through 80° , measured from the torso axis forward, produced: 1) a migration of the group average center of gravity along a curved path of 2.15" arc length; 2) a consistent rotation of the axis of maximum individual variability from $10^{\circ}53'$ aft of the torso axis to a maximum forward angle of $90^{\circ}16'$; and 3) a characteristic fluctuation in absolute size of the individual variation about the group average.

The practical applications of these findings to the design of rocket-powered systems (e.g., escape capsules) is discussed in detail.

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BACKGROUND

A recent innovation in ejection seat design for high-speed aircraft is the rocket catapult. Igniting the instant after an exploding charge of gun powder has started the seat and occupant hurtling up guide rails through the opened hatch of a distressed aircraft, the rocket catapult produces a powerful and sustained thrust. This thrust, when aimed in the proper direction, throws the operator and his seat much farther above the aircraft than would the gun powder blast alone.

This additional height assures the operator of clearing the aircraft at high altitude as well as during landing or takeoff. Further, it provides the ejected crewman with additional time for separating himself from his seat in mid-air and deploying his parachute before striking the ground.

The maximum benefit from the rocket can only be realized, however, if it is installed on the seat and aimed correctly. The line or vector of force on the seat produced by the thrust of the burning rocket exhaust gases must be oriented very carefully with regard to the center of mass of the seat-with-man if it is to carry its human passenger to a safe altitude above the disabled aircraft.

A basic design problem exists then of determining the locus of the seat-man center of gravity. More particularly, since details of seat hardware can change during the course of the evolution of a given design, there exists the problem of determining the center of gravity of the man, per se.

Concerning the man's center of gravity, however, certain complications arise. Biological organisms such as man, unlike the inanimate entities of ejection seat hardware, are not built to close production tolerances insofar as size, shape, and mass distribution are concerned. John Doe, for instance, will not have exactly the same center of gravity relative to a reference point on the seat as will Joe Jones even if they both adopt the same body posture when sitting in the seat.

Thus, we must expect variability in the combined seat-man center of gravity because of the human factor. This variability leads to uncertainty on the part of the designer as to where, exactly, the seat-man center of gravity should be considered to lie for purposes of rocket installation.

Do we aim for John Doe or Joe Jones? The answer is: we aim for neither, but rather both. That is, we take an average. We sample the whole population of which John Doe and John Jones are but two members. The larger the sample the more reliable is the estimate of the "true" average of the population's center of gravity.

Once having obtained a suitable estimate of the average location of man's center of gravity we must then consider the problem of variability about this average—for the "average" is but a statistical abstraction, an arithmetical construct, and it

may be, as often happens, that not a single individual in our sample nor even in the entire population will have a center of gravity falling at exactly the "average" location.

From this, one might suspect that by using such an abstraction as the "average" center of gravity for orienting the ejection seat rocket thrust, a thrust vector would be produced which would not suit anyone exactly. This is indeed true but it nevertheless minimizes over the range of all members of the population the amount of misalignment between the thrust vector and the individual's center of gravity.

If the variability of individual centers of gravity about this average is sufficiently large as to cause serious misalignment in a high percentage of the expected cases, modifications must be made in the design of the ejection seat to compensate, perhaps aerodynamically, for this dangerous possibility.

In this, however, it should not be taken for granted that the ambient (existing at the instant of rocket ignition) acceleration is constant either in amplitude or direction of its action on the human body. Rather, it should be recognized that the changes in velocity and/or direction of movement, which are constantly occurring in normal aircraft flight and which are often tremendously amplified in an emergency condition, will produce considerable variability in the ambient acceleration field.

This variability in ambient acceleration introduces further uncertainties about both the individual's center of gravity and about the mean center of gravity of the whole population of individuals.

The effects of changing acceleration on the spatial distribution of the parts of one's anatomy relative to one another are easily imagined. When one "stands" on one's head the direction of acceleration due to the earth's gravity is changed through an arc of 180° and although, to the writer's knowledge, no one has ever measured the exact amount involved, the resultant sensations of hollowness in the abdomen and congestion in the head (a situation which is unfortunately all too often the reverse of normal) seem to indicate a marked shift in the body's mass, and therefore the center of gravity, toward the head.

Certainly no one would question the obvious association - nay, even actual causal relationship - between this well-known subjective phenomena and the change in direction of the acceleration of the body.

A similar phenomenon occurs when a vehicle such as an automobile or airplane in which we are riding changes either the direction in which it is moving or the velocity at which it is moving, or both.

A change in the vehicle's velocity alone means that the auto or aircraft is accelerating (increasing its velocity) or decelerating (decreasing its velocity) but in a constant direction. We, the passengers, tend, if not supported by a seat or restrained by belts, to continue moving at the original velocity of the vehicle.

The body support or restraint harness fastening us to the vehicle forces our body to do otherwise, i.e., change our velocity in conformance with the vehicle's change in velocity.

If the support and restraints are well designed and correctly adjusted to our body the major portions of our anatomy will change velocity with the vehicle. Inside our bodies however things do not conform so nicely to the vicissitudes of vehicular movement.

The bodily fluids, as well as certain loosely attached internal organs, cannot be strapped to the seat like our arms, legs, head and torso. They are relatively free to continue traveling at the original velocity. As a result there is a physical movement between the main body structure, which does change velocity, and the internal anatomy which does not - at least at first.

That is, the main body structure tends to move on, leaving the "internal workin's" behind so to speak. If the change in vehicle and main bodily structure velocity is great enough and abrupt enough the "left behind" effect can be sufficiently

great as to cause the internal organs to tear loose from their relatively weak supports and the body fluids, notably the blood, to burst out of their elastic containers - all with detrimental even fatal results. As the saying goes, "its not the fall that hurts; it's the sudden stop"!

This saying actually refers, of course, not so much to a change only in velocity, which implies a constant acceleration due to earth's gravity, as it does to a change in the amplitude of acceleration - a considerable change which goes from 32 ft/sec² to 0 ft/sec² and rather abruptly at that.

It illustrates nevertheless that a uniform change in velocity (i.e., with constant acceleration) and a change in the change of velocity (i.e., a changing acceleration) both produce pronounced shifts in the internal anatomy with respect to the main body structure. Since the internal anatomy has mass it follows that there is thus a change in the body mass distribution, and, therefore, a concomitant change in the mean center of mass namely, the center of gravity.

In a similar vein of intuitive reasoning it follows that a change in the direction of vehicular and accompanying main body structure velocity produces an acceleration (or deceleration) which again produces a movement of the internal anatomy relative to the main body structure. There is thus a shift in body mass distribution and therefore a change in the body's center of gravity.

This effect due to change in direction of movement (or change in direction of acceleration) occurs then not only when one performs "stunts" (like standing on the head) but when the vehicle in which one rides does "stunts" - particularly when such "stunts" are violent.

It is this subtle and invisible shifting of the center of gravity inside the individual in response to changes in ambient acceleration that gives rise to the additional uncertainties in locating a given individual's center of gravity and the mean center of gravity of the whole population of individuals.

In order to initially explore the role in human center of gravity shifts played by changes only in the direction of the acceleration vector, an experimental program has been conducted on a sample of 25 individuals, wherein the angle in which an acceleration vector of one "g" constant amplitude intersected the subject's torso was varied while the subjects were strapped in a slightly modified ejection seat. The resulting measurements of both the individual and sample average center of gravity for each direction of acceleration comprise the subject of this report.

APPROACH

The approach taken in this exploration of the effects of shifting accelerational forces on human centers of gravity was limited to tests in the 1" g acceleration field imposed by the normal gravitational attraction of the earth.

The direction of this constant-amplitude acceleration vector was varied in increments from an initial angle 15° forward of the rump-to-head torso axis through a range of 65° , to a final angle of 80° forward of the torso axis, or within 10° of being perpendicular to the torso axis.

This was experimentally simulated by varying the orientation of a rigid body support structure from a condition in which the back support and torso axis were parallel and 15° aft of vertical (i.e., the gravitational vector), through convenient increments, to an orientation wherein the back support (and torso axis) formed an 80° angle (toward the rear) of vertical. The 15° aft conditions might represent normal straight and level flight while the 80° condition might represent either non-uniform flight of one "g" acceleration or near-vertical "flight" of a space craft.

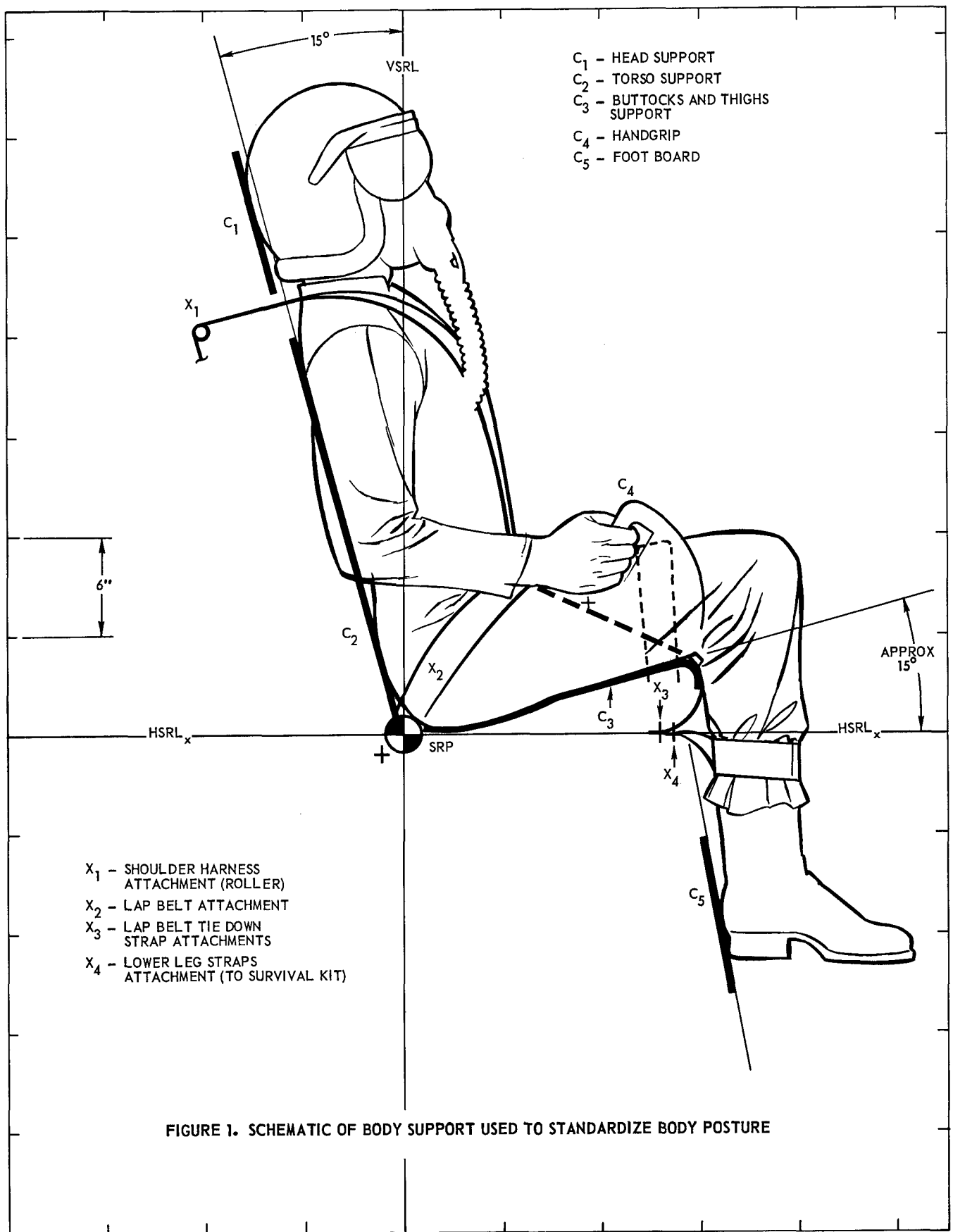
Since variability in the initial body posture or geometry assumed by each subject produces a considerable effect upon the variability or "scatter" of observed centers of gravity for a given "g" vector, every attempt was made to standardize the body posture tested and thereby hold it relatively constant from

subject to subject. The posture is shown schematically in Figure 1. This effort was facilitated by using the body support schematically illustrated in Figure 1 and photographically depicted in Figures 2 and 3.

Figure 1 is drawn to scale with a 6-inch grid outlined around the margins to accurately describe the body support used. The head (via the crash helmet) at C_1 , and thorax and pelvis at C_2 were contact areas which lay essentially in a plane that intersected the Vertical Seat Reference Line (VSRL passing through Seat Reference Point (SRP)) at an angle of 15° aft of VSRL. This plane is the seat back support surface.

The buttocks and to some extent the thighs received support from a contoured, fiberglass, survival kit top (C_3) which was covered by a two-inch polyurethane cushion. Because of the complex configuration of this molded surface only an approximate angle can be given for the plane of actual body support. This is estimated at being about 15° above the Horizontal Seat Reference Line ($HSRL_x$).

For these tests the ejection seat was modified to provide a foot board (C_5) for support of the feet against fore-aft movement. Movement of the legs was also limited by short straps of constant length, passing from the front of the buttock support surface (i.e., from X_3 on the survival kit), to stout cuffs buckled about the lower legs just below the bulge of the calf.



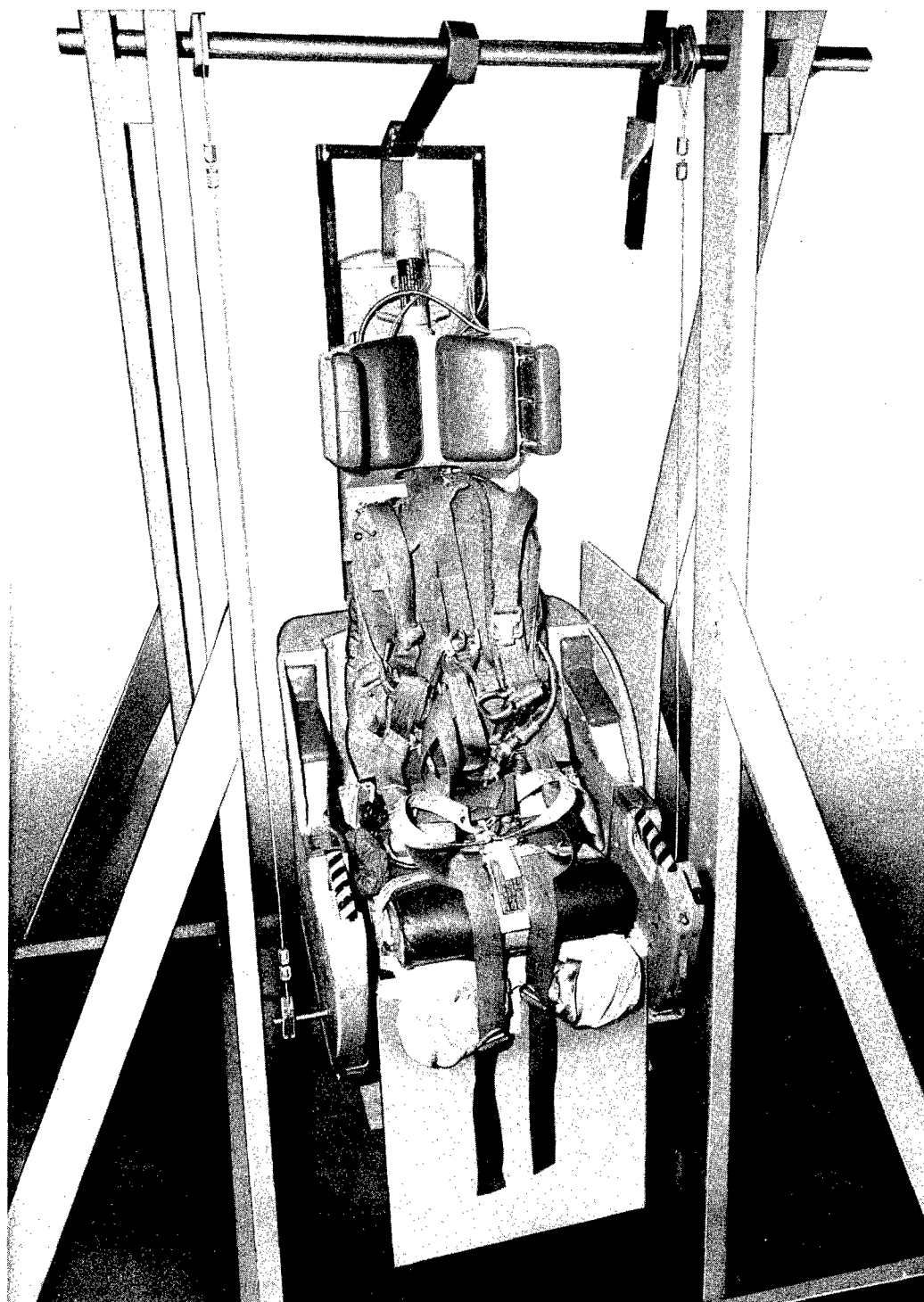


FIGURE 2. BODY SUPPORT (EJECTION SEAT) AND RESTRAINT HARNESS



FIGURE 3. NORMAL EJECTION POSTURE BODY RESTRAINTS IN PLACE

The legs hung, in fact, from these straps which, because of their short length, kept the knees of many subjects slightly elevated above the seat cushion. The extent to which the knees were thus elevated was dependent upon how the lower leg cuffs positioned themselves on the subject's calf and was as a result somewhat less controlled from subject-to-subject than other aspects of the body posture. Specific hardware design considerations dictated this rather unstable method of limiting leg movement.

The handgrip (C_4) was the only other point of bodily support in this test.

To further ensure constancy of body posture a variant of the standard body restraint of modern high-performance aircraft was used. This consisted of shoulder harness attached at X_1 , lap belt attached on either side at X_2 , a lap belt tie-down strap, attached to the survival kit between the legs at X_4 and a thigh restraint strap attached to the seat at X_3 . The latter is not widely used in ejection seats.

So that the human body center of gravity data obtained from this study would reflect the conditions of actual flight, three items of the operator's personal equipment were included. These were the standard Air Force type P-4 crash helmet, the standard oxygen mask, and flying boots. The same helmet and oxygen mask were worn by all subjects because only one such ensemble was

available. For the same reason, only three different sizes of boots were used.

Civilian clothing reasonably comparable to the Air Force summer flying coveralls in total weight and mass distribution was worn by all subjects. No attempt was made to closely control this variable except that each subject wore the exact same clothing for all experimental conditions.

Twenty-five (25) male subjects were selected for testing according to a stratified sampling plan based upon the distribution of stature described (Ref. 1) for the Air Force flying population of 1950. Twenty-five stature strata (one subject per stratum to simplify statistical weighting) were defined by limits so selected that four percent of the flying population would be expected to fall within each strata.

Stature was selected as a useful stratification criterion because of the findings of Air Force investigators (Ref. 2) that it was more consistently related to the other linear body segment measurements than any other single easily obtained measurement.

In Table I, column 2, are listed the midpoints for the criterion strata. In column 3 the actual stature observed on each subject is given. Column 4 presents each clothed subject's weight wearing boots, helmet and oxygen mask.

TABLE I

Ideal Requirements for Stature Strata Compared With Observed
Stature and Weight of Twenty-Five Test Subjects

IDEAL STRATA		SUBJECTS	
1	2	3	4
No.	Midpoint	Stature	Weight (with boots and helmet)
1.	64.1"	63.9"	126 lbs.
2.	65.3	65.6	157
3.	66.0	66.1	171
4.	66.5	66.2	162
5.	66.9	66.9	161
6.	67.2	67.0	164
7.	67.6	67.6	213
8.	67.8	67.9	195
9.	68.1	68.1	128
10.	68.4	68.4	162
11.	68.6	68.6	179
12.	68.9	69.0	185
13.	69.1	69.2	179
14.	69.4	69.3	182
15.	69.6	69.7	201
16.	69.9	69.8	161
17.	70.1	70.1	182
18.	70.4	70.3	177
19.	70.7	70.6	185
20.	71.0	71.1	197
21.	71.4	71.6	169
22.	71.8	71.9	187
23.	72.3	72.4	161
24.	72.9	72.8	221
25.	74.2	74.1	198

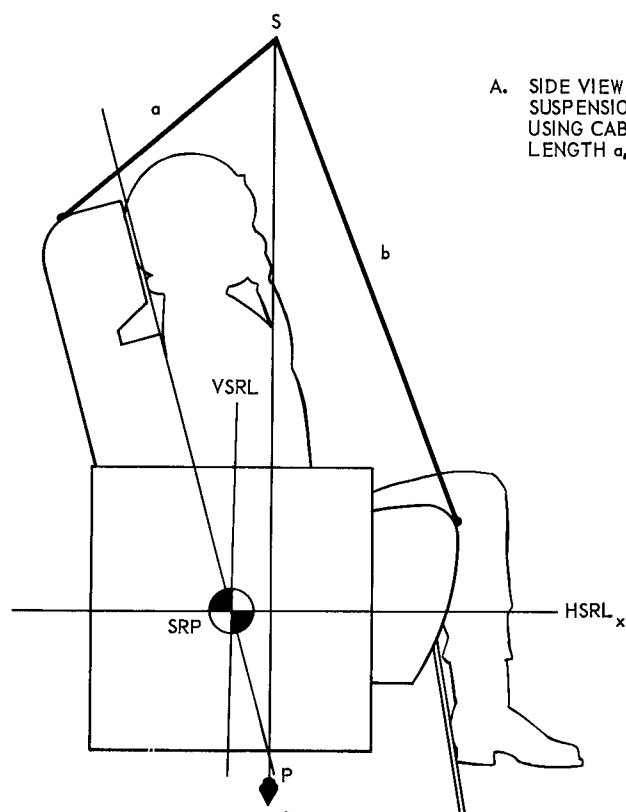
METHOD AND APPARATUS

The center of gravity of any rigid body, no matter how complicated its shape, can be found experimentally in several different ways. All methods stem from the common concept of varying the body's orientation with respect to gravity. Of these techniques the suspension method is one of the most accurate and certainly the simplest in respect to the equipment required. For these reasons, it was chosen in a previous ad hoc study by Air Force workers (Ref. 3), although previous as well as subsequent limited studies have employed a balancing method (Refs. 4 and 5).

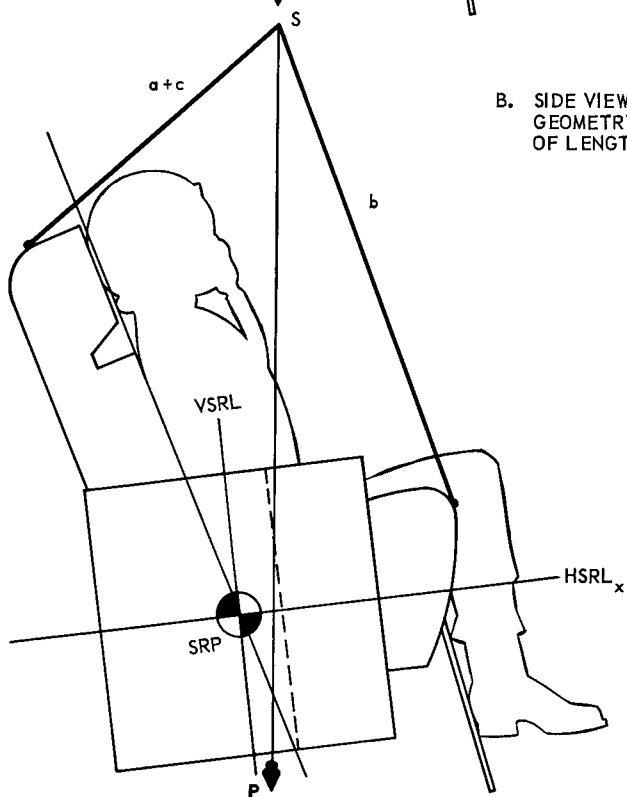
The suspension method requires, when determining only two coordinates of the center of gravity (such as was done in the present case), simply that the object of interest be freely suspended like a porch swing from a single overhead axis, as shown in Figures 4, 5, and 6, together with a plumb line.

In Figure 4A the seat-man mass and plumb line (SP) are suspended from an overhead bar at S by means of bearings.

Since the center of gravity of the suspended seat-man mass as well as that of the plumb-bob will both seek a position in space directly below their common suspension at S, the plumb line will pass through the seat-man center of gravity as seen from a side view.



A. SIDE VIEW OF SUSPENSION GEOMETRY USING CABLES OF LENGTH a , AND b RESPECTIVELY.



B. SIDE VIEW OF SUSPENSION GEOMETRY USING CABLES OF LENGTH $a+c$, AND b RESPECTIVELY.

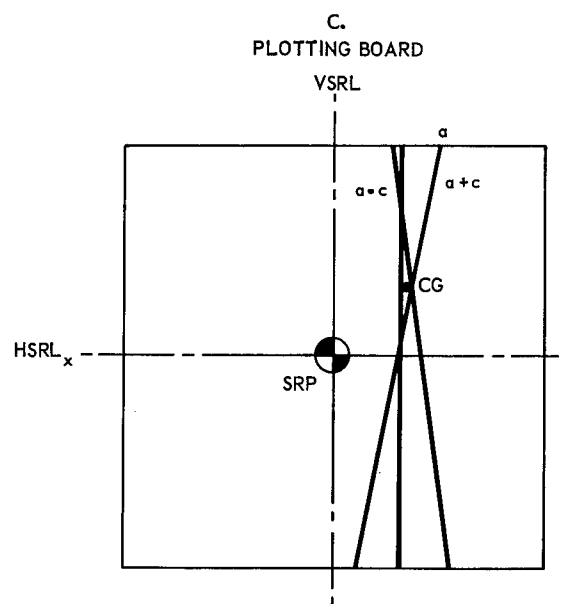


FIGURE 4. SUSPENSION METHOD OF LOCATING SEAT-MAN CENTER OF GRAVITY

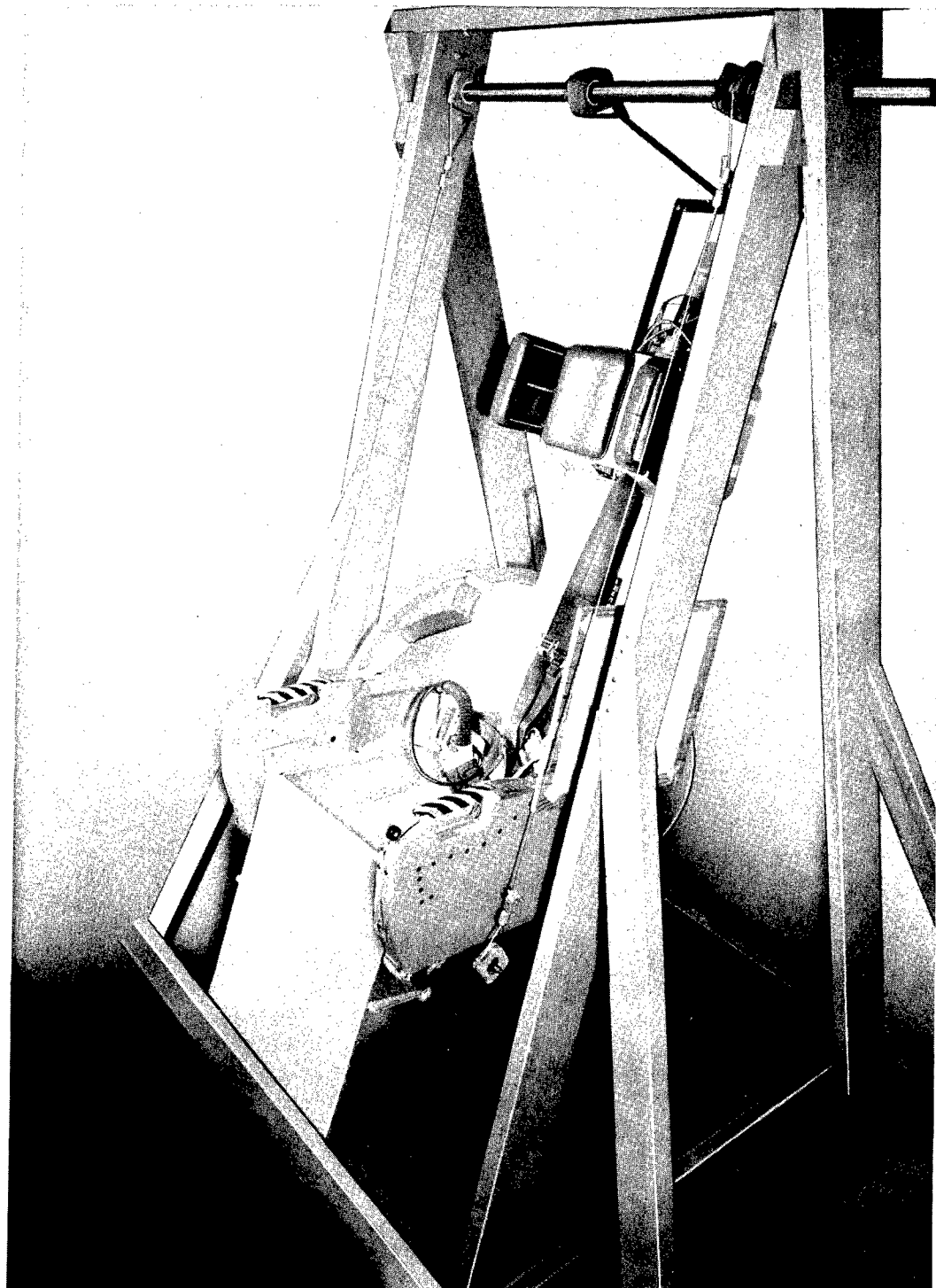


FIGURE 5. EMPTY EJECTION SEAT

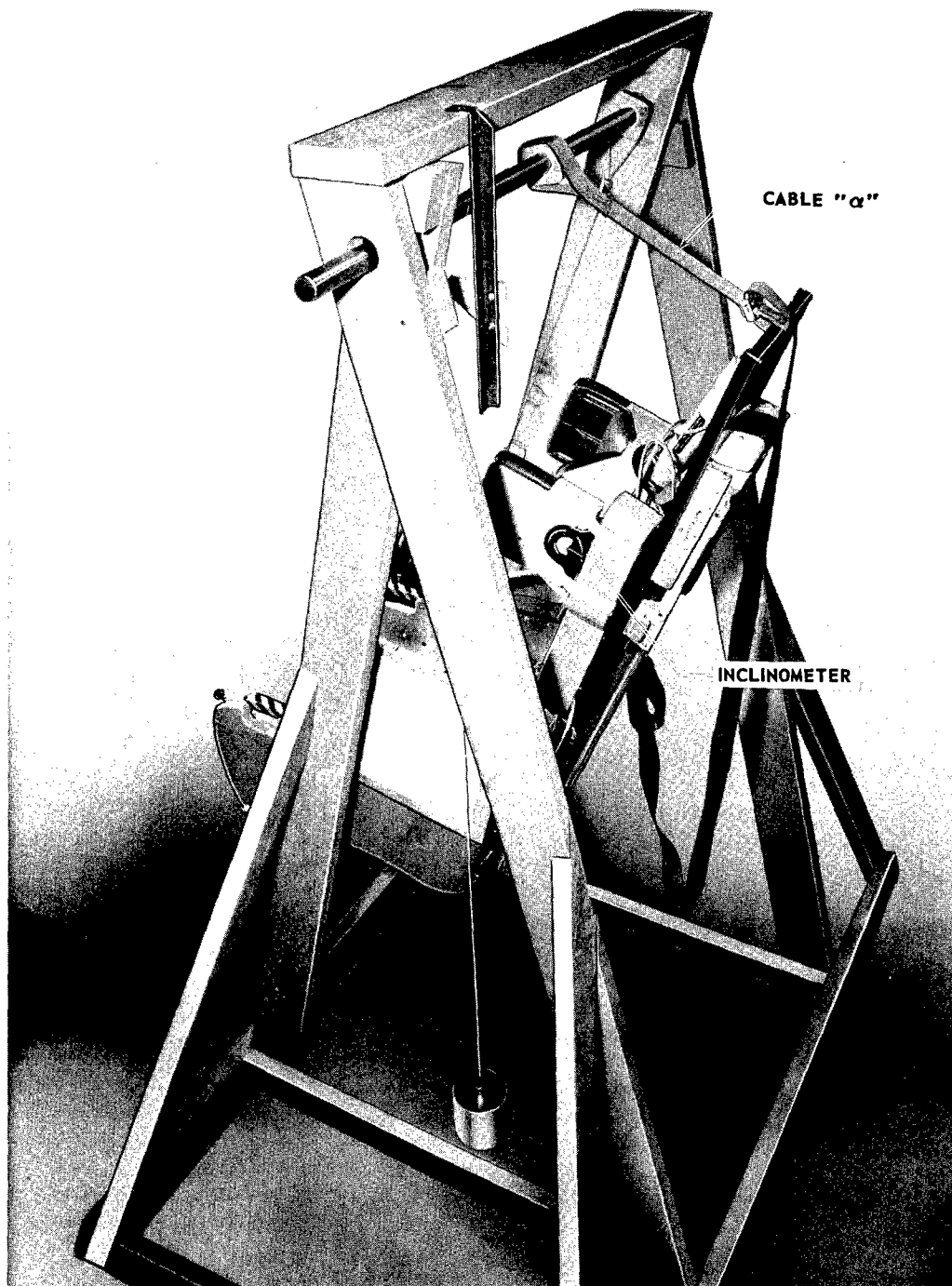
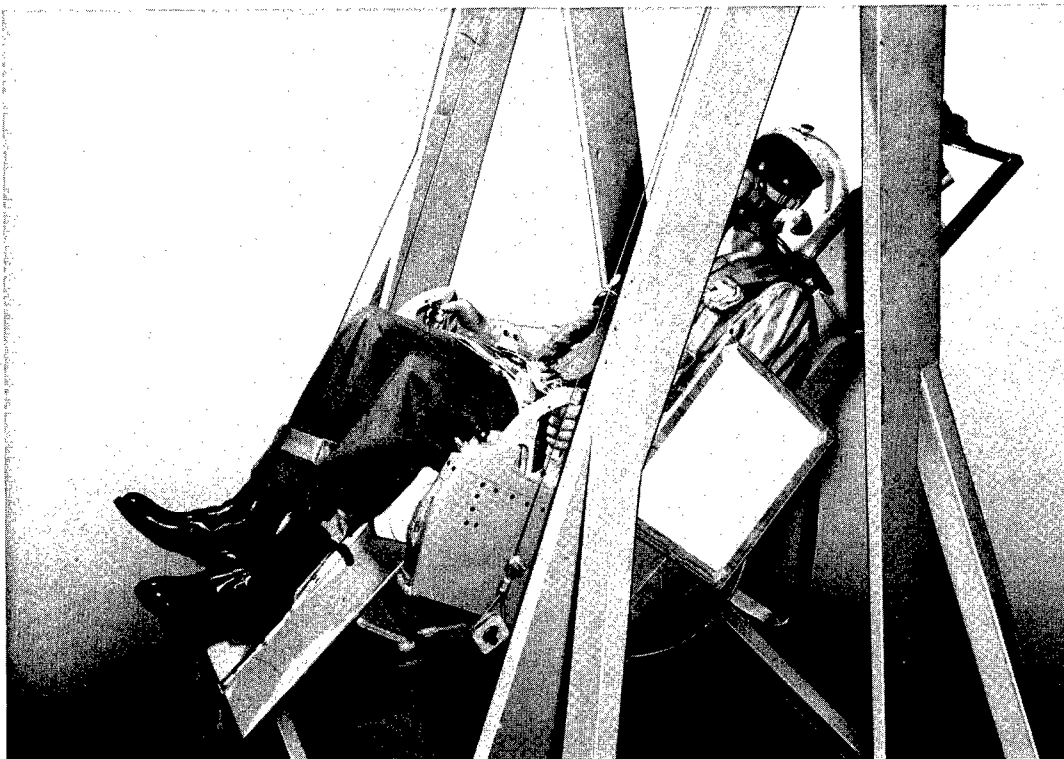


FIGURE 6. EMPTY EJECTION SEAT WITH INCLINOMETER POSITIONED FOR MEASURING SEAT ANGLE TO THE VERTICAL
NOTE: PLUMB BOB EMERSED IN CAN OF OIL TO DAMP OSCILLATIONS.

A



B



FIGURE 7 PROGRESSIVE TILTING OF SEAT TO SIMULATE CHANGE IN DIRECTION OF ACCELERATION VECTOR



FIGURE 8. BACK ANGLE OF 80° AFT OF VERTICAL TO SIMULATE AN ACCELERATION VECTOR AIMED AT 80° FORWARD OF BODY TORSO AXIS.
NOTE: PLOTTING BOARD AND PLUMB BOB IN OIL BATH FOR DAMPING

Using suspension cables of length "a" and "b" respectively (Figure 4A) the plumb line is projected upon a plotting board, which is securely mounted to the seat as illustrated here and in Figure 8.

Now when cable "a" is lengthened by amount "c" the seat-man mass will swing about "S" to seek a new position such that its center of gravity will once again be directly below the suspension about "S," as shown in Figure 4B.

The plumb line will of course remain unaffected by this change in the length of suspension cable "a."

By again projecting the plumb line onto the plotting board in the configuration shown in Figure 4B we obtain another line through the seat-man center of gravity.

By once again changing the length of "a" to "a-c," we may obtain a third projection of the plumb line through the seat-man center of gravity. The intersection of these three lines will seldom be a point, but will instead delineate a small triangle such as shown in Figure 4C. The center of this triangle will be an accurate estimate of the true location, in two dimensions, of the center of gravity (abbreviated as CG).

Figures 2, 3, 5, 6, 7 and 8 show the actual experimental rig for using the suspension method of locating the seat-man center of gravity in this study. Figures 5 and 6 show the empty ejection seat and Figure 2 shows the same seat provided with

standard Air Force back-type parachute, survival kit, seat cushion, and necessary body restraints. Figures 7 and 8 show the seat and subject at various simulated angles of the acceleration vector.

Suspending the plumb-bob in a can of machine oil was helpful in damping small oscillations due to accidental blows to the suspended seat during the experiment.

PROCEDURE

Using this suspension method, the x (parallel to the HSRL_x)* and z (parallel to the VSRL)* coordinates of each subject's center of gravity were determined in the following manner.

Each individual donned helmet, oxygen mask, and boots, and was strapped into the seat (Figure 3).

The length of cable "a" (Figures 4 and 6) was adjusted until the seat back support structure formed an angle (opening to the rear) of 15° with vertical as measured by an inclinometer mounted on the seat back (Figure 6). The plumb line was projected by two pin pricks upon the plotting board, after which the cable "a" was shortened to rotate the seat forward until the seat back formed a rear-opening angle of only 10° with the vertical. The plumb line was again projected upon the plotting board.

Finally, the length of cable "a" was increased until the seat rotated to the rear far enough so that the seat back support formed an angle of 20° to the rear of vertical. The plumb line was then projected for the third time upon the plotting board.

In this manner were three mutually intersecting lines, each passing through the seat-man center of gravity, obtained on the plotting board. This intersection defined a small triangle, the center of which represented an estimate of the seat-subject's

* See References 6 and 7 for a discussion of the use of these reference lines in cockpit design.

center of gravity for a back support inclined at a nominal angle 15° aft of vertical. This simulated an acceleration vector inclined 15° forward of the back support and the subject's torso axis.

Next the length of cable "a" was further lengthened to produce a 30° seat back angle aft of the vertical and the plumb line again projected upon the board. The intersection of this line and those previously projected at the 10° and 20° back angles formed another triangle whose center represented an estimate of the seat-man center of gravity for a seat back support tilted at a nominal angle 20° aft of vertical (or a simulated acceleration vector inclined 20° forward of the back support).

The length of cable "a" was again lengthened to yield a back support angle of 40° aft of vertical and the plumb line once again projected. In combination with the 20° and 30° lines previously projected this estimated the seat-man center of gravity when the back support was inclined at an angle of 30° aft of vertical (or for a simulated acceleration vector inclined 30° forward of the back support surface).

This process was continued for seat back angles of 50° , 60° , 70° , 80° and 90° aft of vertical, yielding in a similar manner the additional estimates of the seat-man center of gravity for 40° , 50° , 60° , 70° , and 80° seat back angles respectively, or 40° , 50° , 60° , 70° and 80° inclinations of the acceleration vector forward of the back support and subject's torso axis.

Thus, for each of the twenty-five subjects there were obtained eight estimates of the center of gravity of the seat-man combination, one at each of eight different seat tilts or - as we originally desired - eight different directions of a 1 "g" acceleration vector. These conditions are illustrated in schematic form in Figures 9, A and B.

Figure 9A shows the back angles tested based upon a vertical line (i.e., gravitational acceleration) through SRP. Figure 9B shows the acceleration vectors (dashed lines) simulated as measured from the back support (torso long axis), together with the corresponding subjectively felt "g" (inertial) vectors (solid lines).

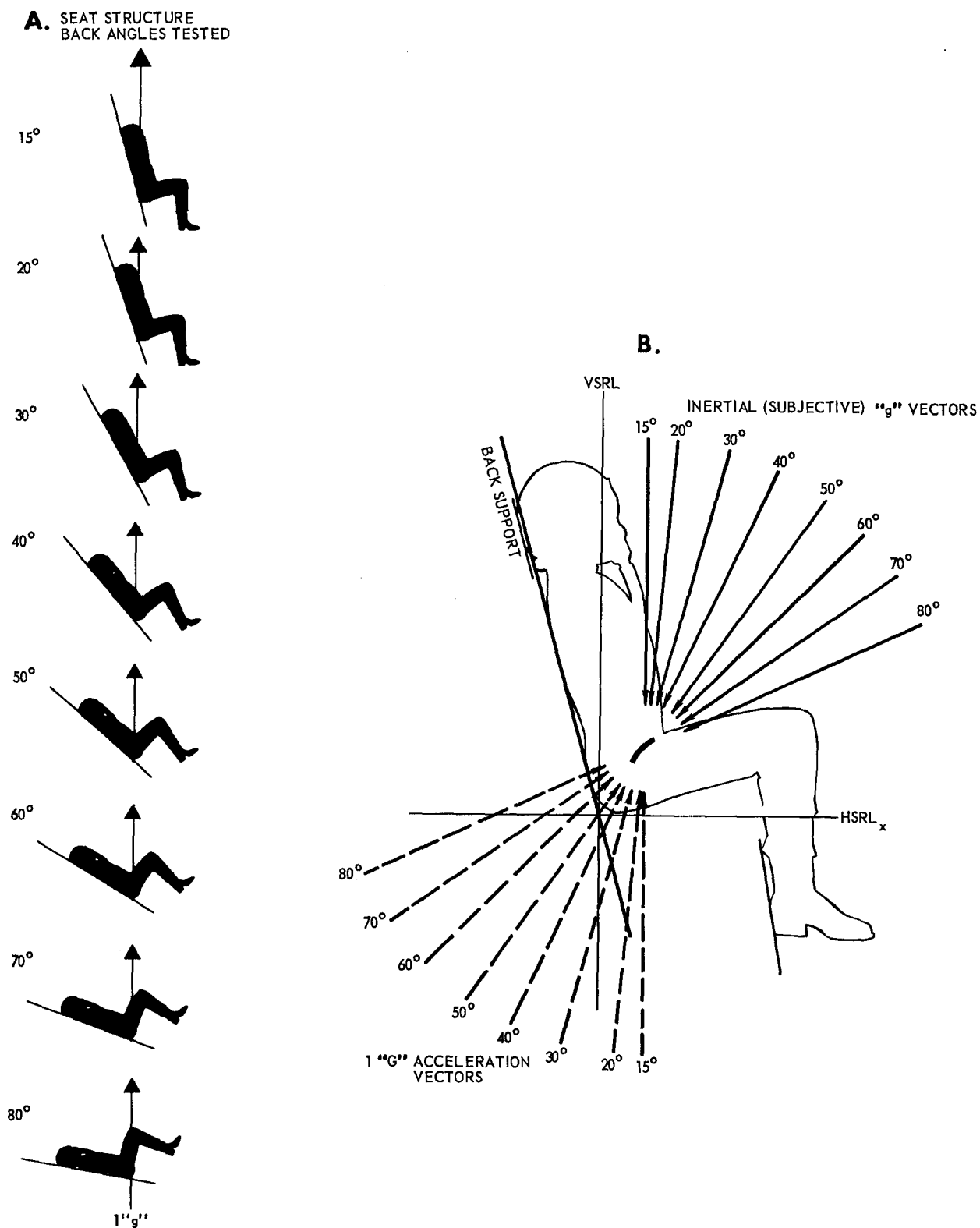


FIGURE 9. A. SCHEMATIC OF THE EIGHT ORIENTATIONS OF THE MAN-SEAT MASS WITH RESPECT TO THE CONSTANT 1 "g" GRAVITATIONAL ACCELERATION

B. 1 "g" GRAVITATIONAL VECTORS EXPERIMENTALLY SIMULATED AND CORRESPONDING SUBJECTIVE OR INERTIAL "g" VECTOR - BOTH WITH RESPECT TO THE BACK SUPPORT (OR LONG AXIS OF THE TORSO).

RESULTS

In order to examine the basic phenomenon of human center of gravity changes accompanying changes in the direction of a one "g" acceleration vector, the combined man-seat center of gravity data were transformed so as to remove the unique effects of the seat: both its mass-distribution and its total mass.

The transformed data are thus independent of the particular hardware used to position the body in the test posture. They describe the x and z coordinates for the center of gravity of the human body per se in the posture described, lightly clothed, and wearing boots, helmet, and oxygen mask.

These data are presented for each direction of the acceleration vector in Figures 10 through 17. Each of these figures shows the individual (transformed) centers of gravity of 25 subjects plotted with reference to the VSRL and HSRL_x coordinate axes shown in Figure 1. Henceforth, these two lines will be called the z and x axes through SRP, respectively.

In each of these eight figures the vertical line marked $\bar{X}$ is the arithmetical average of the x coordinates of the twenty-five centers of gravity while the horizontal line marked $\bar{Z}$ is the arithmetical average of the 25 z coordinates. These two perpendicular lines intersect at the centroid of the cluster of individual centers of gravity in each figure. This centroid is the average

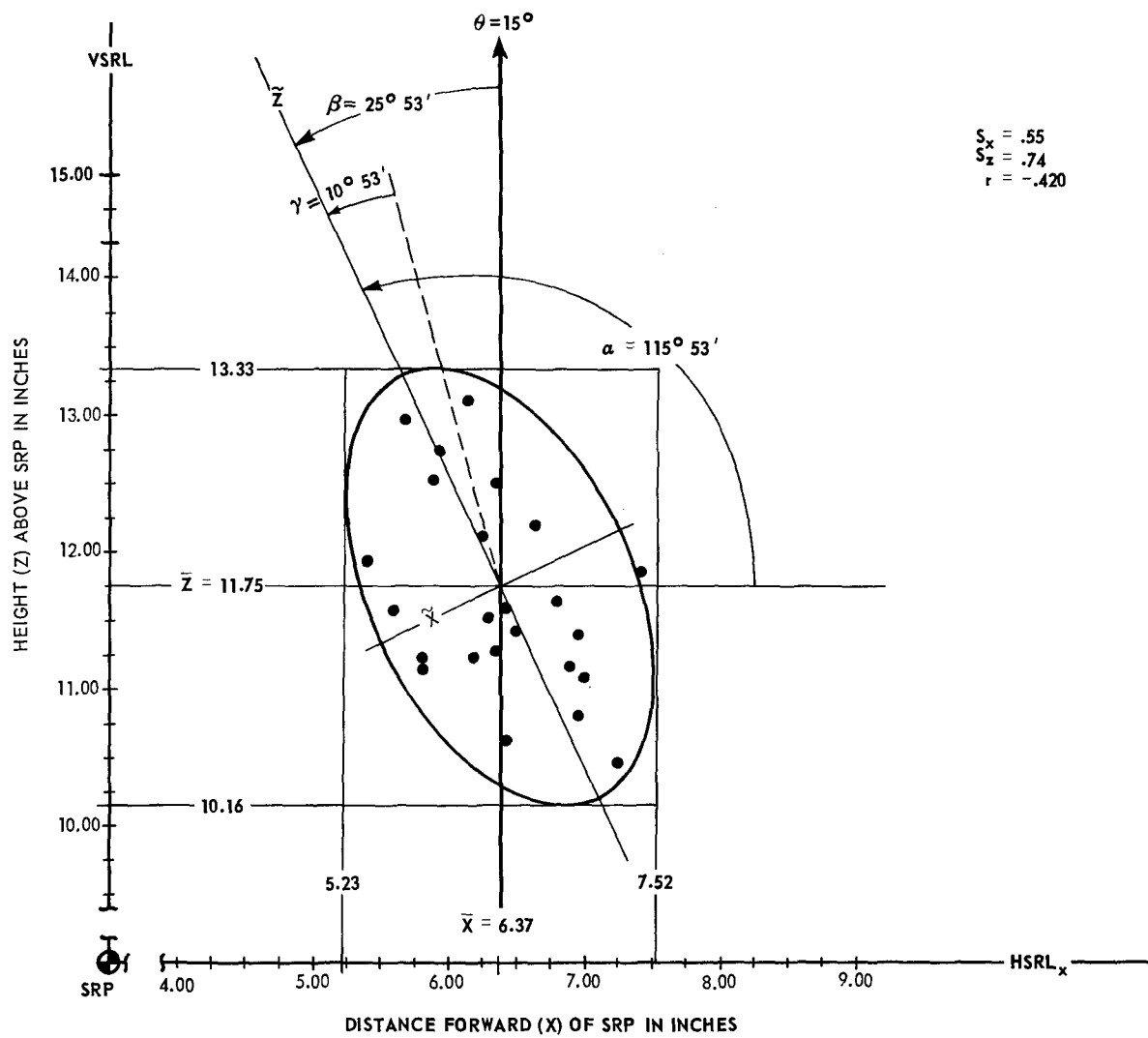


FIGURE 10. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 15° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

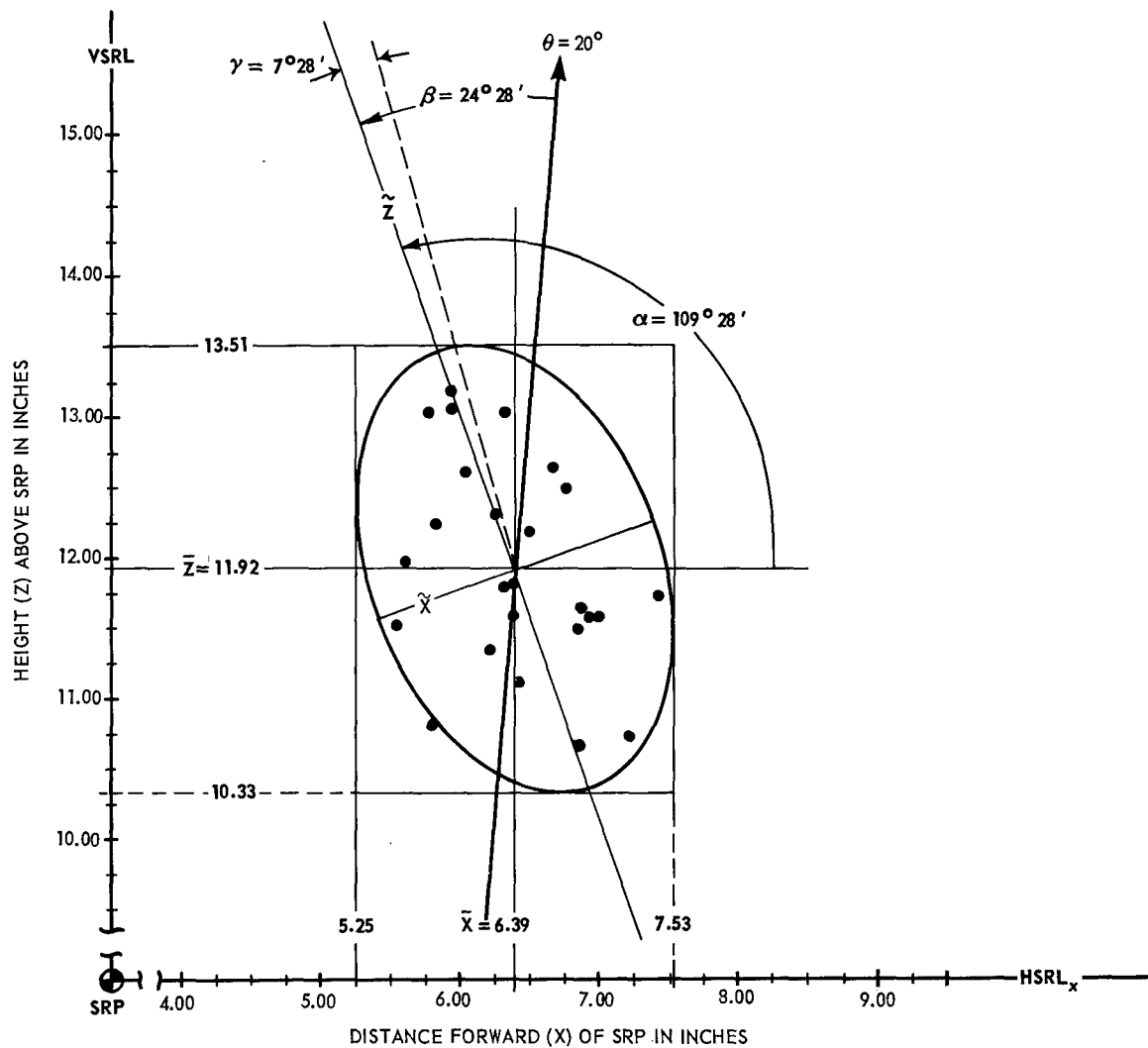


FIGURE 11. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 20° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

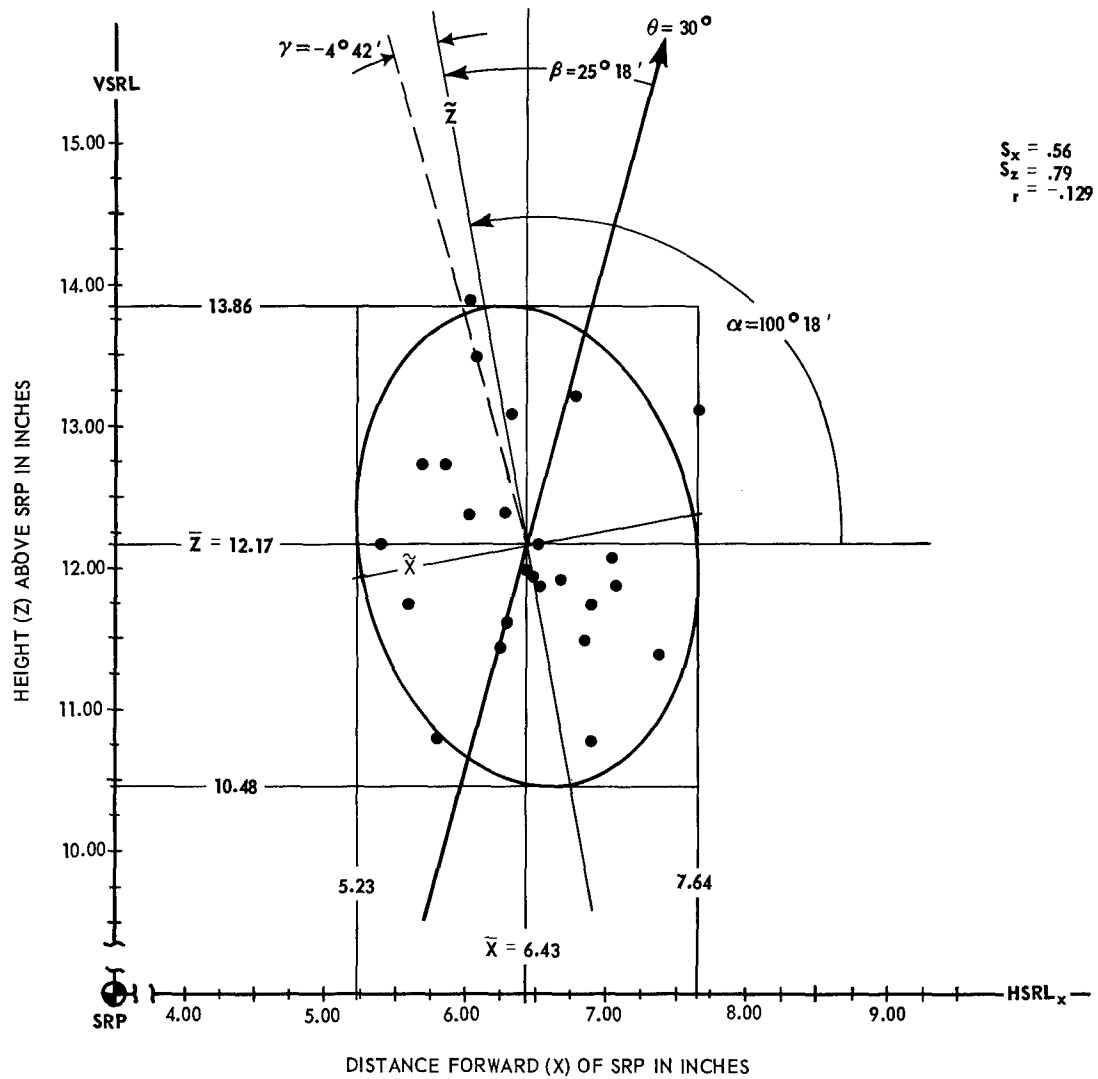


FIGURE 12. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 30° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

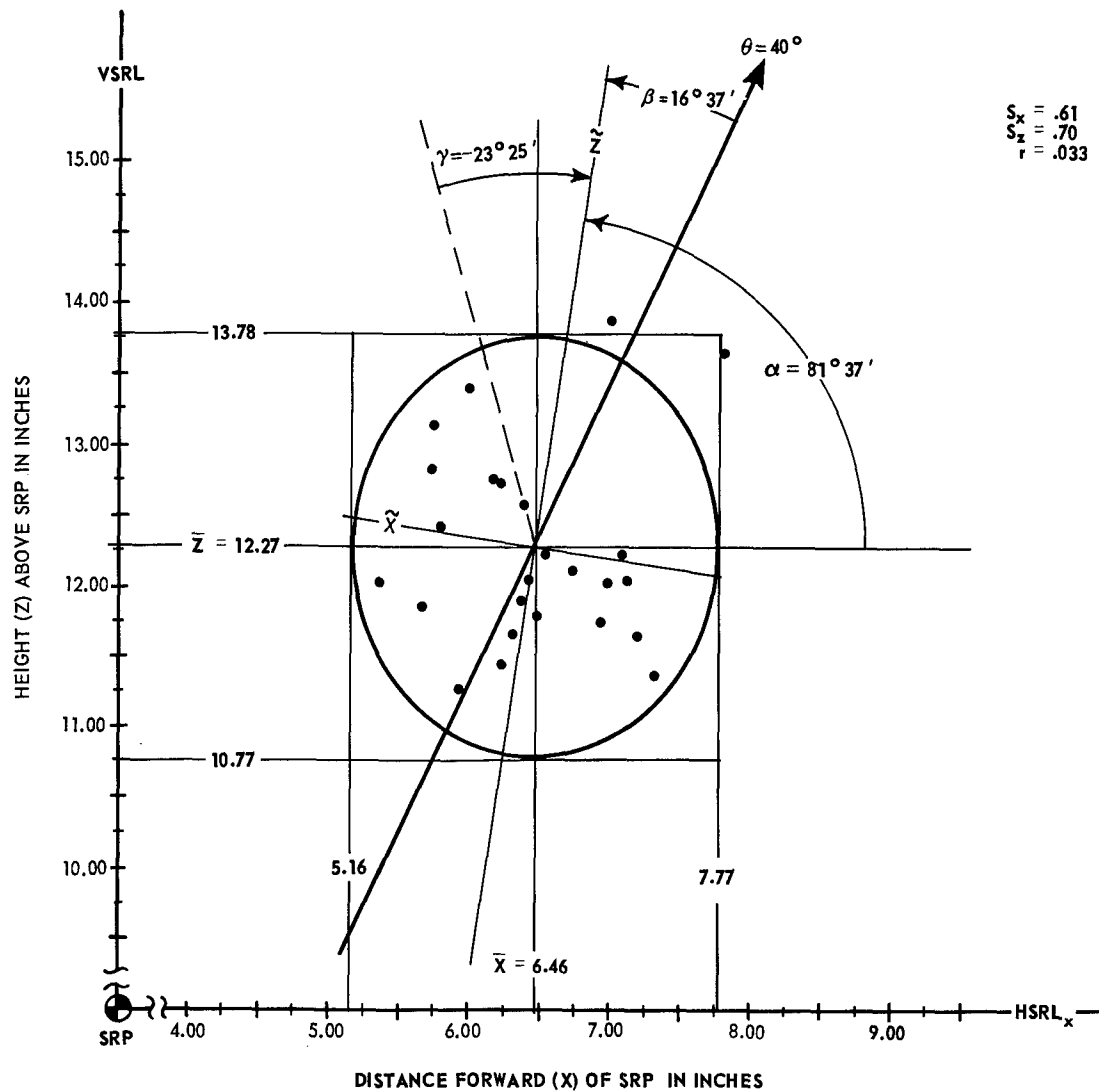


FIGURE 13. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 40° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

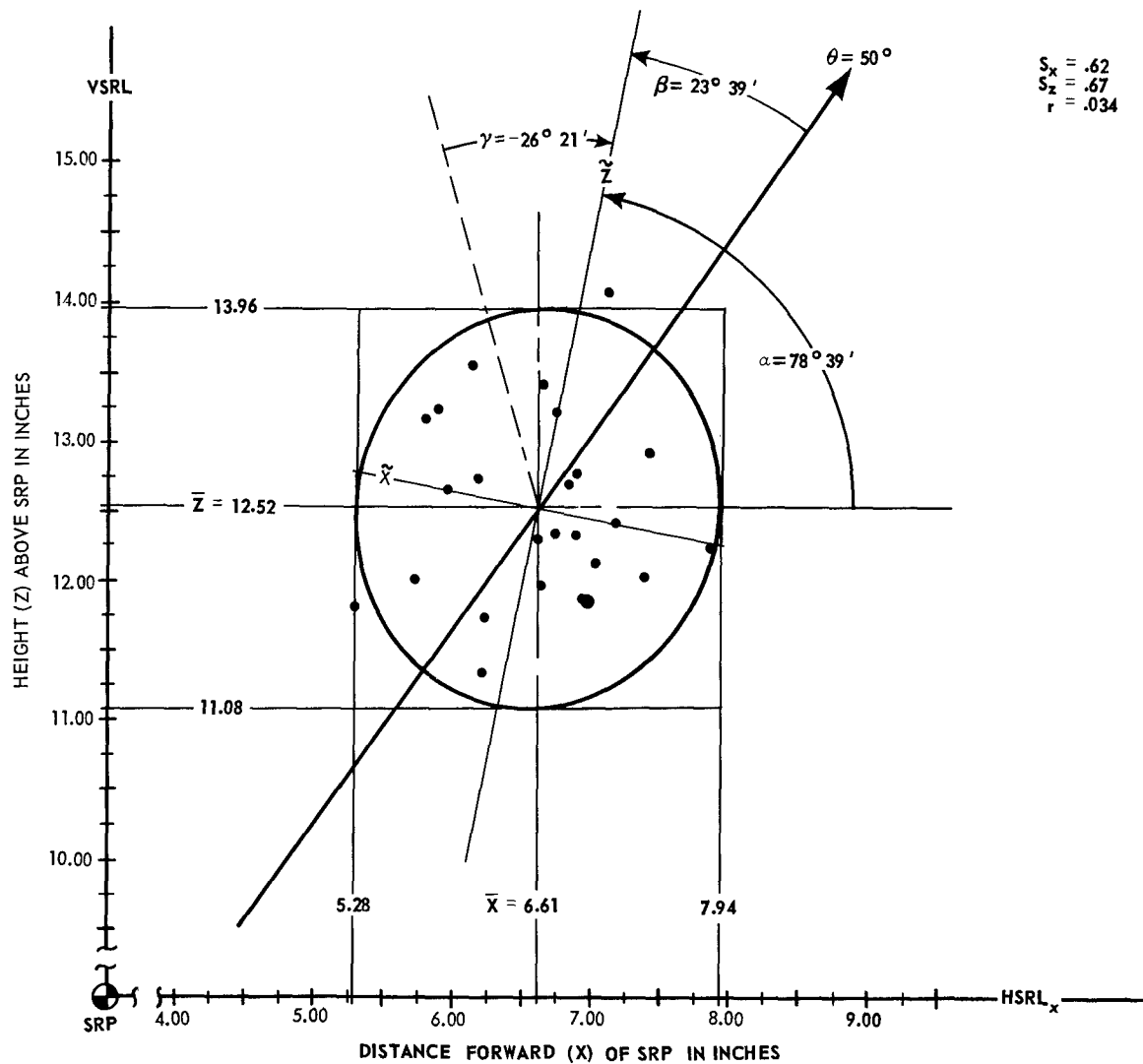


FIGURE 14. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 50° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

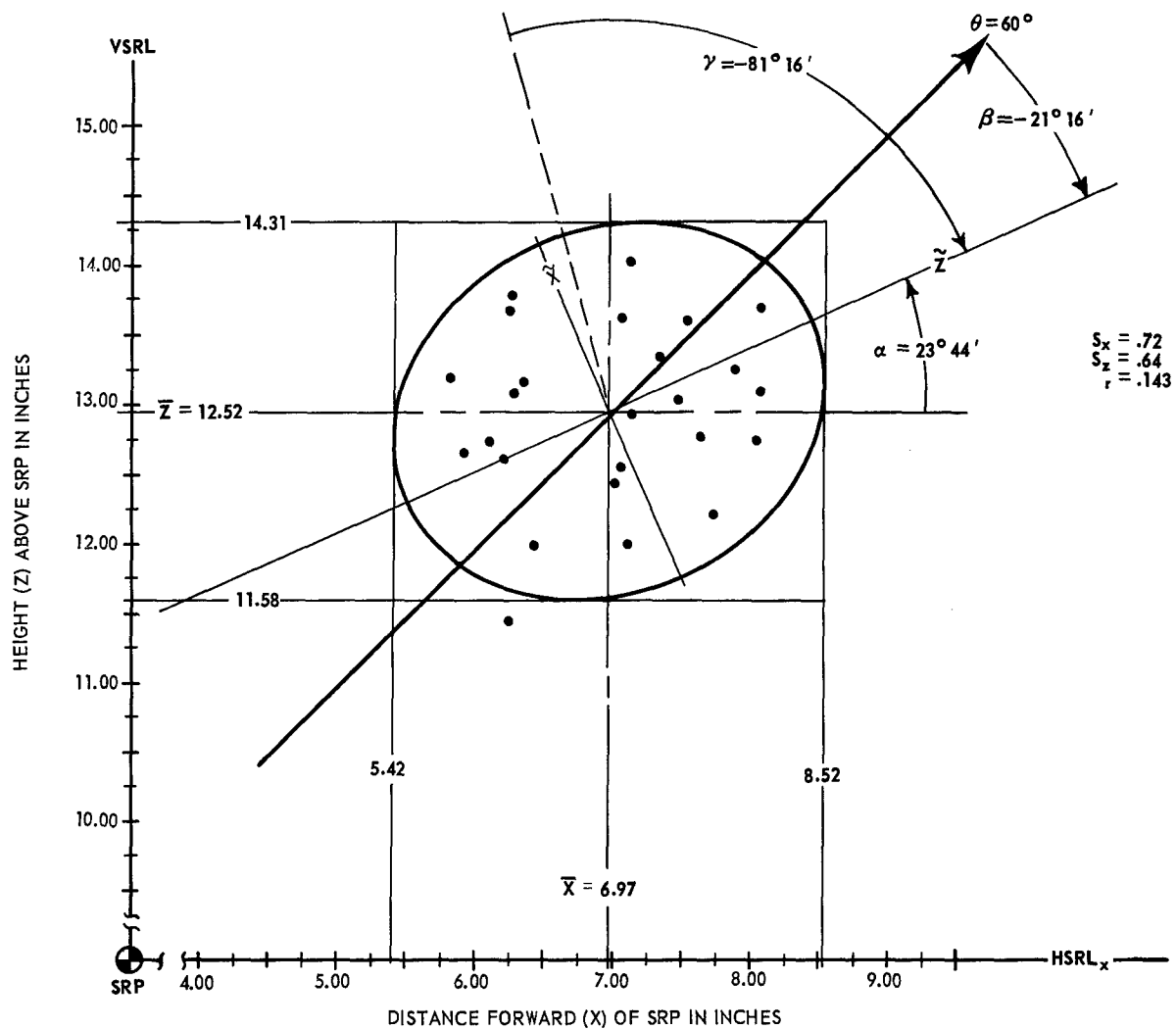


FIGURE 15. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 60° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

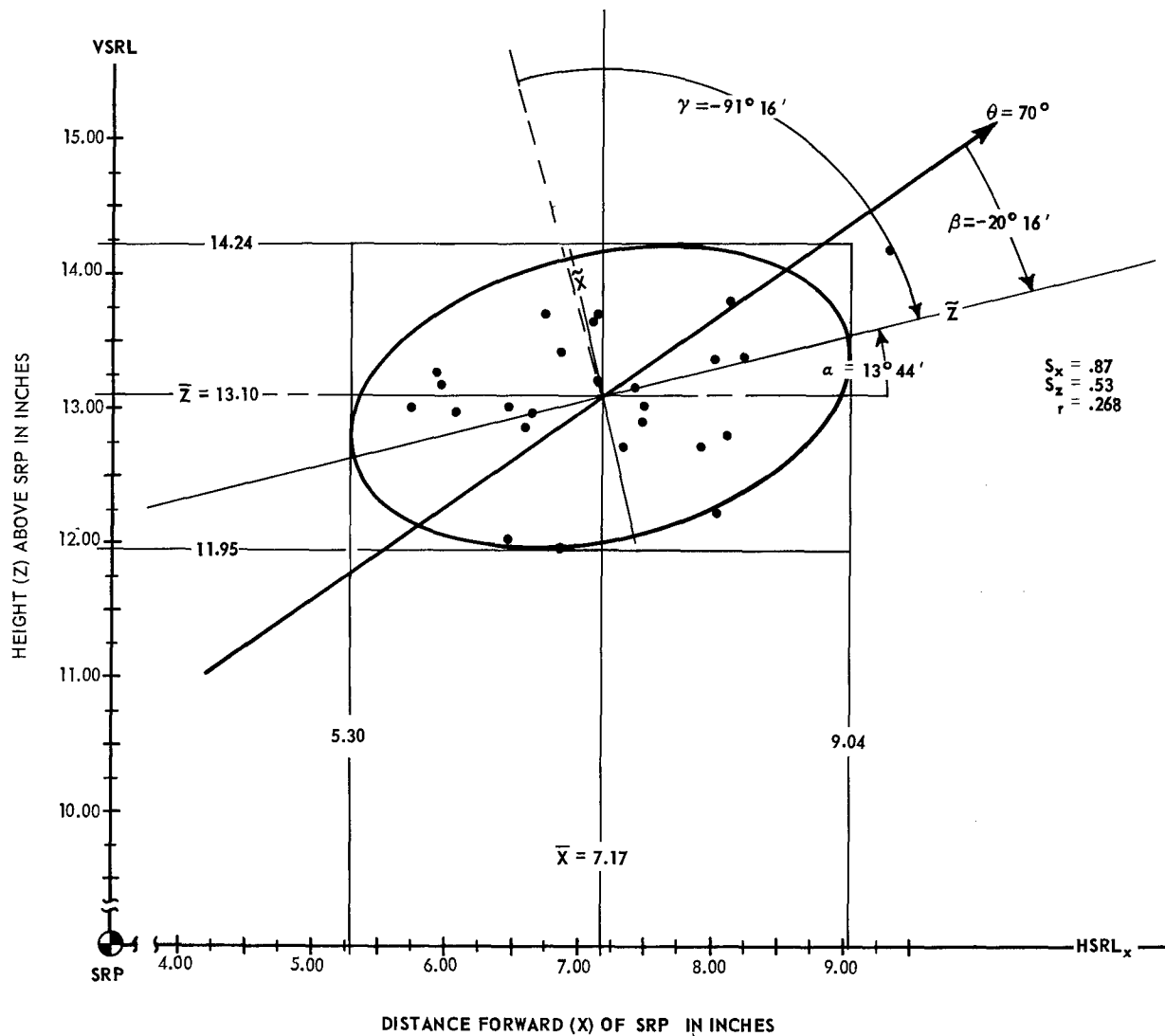


FIGURE 16. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 70° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

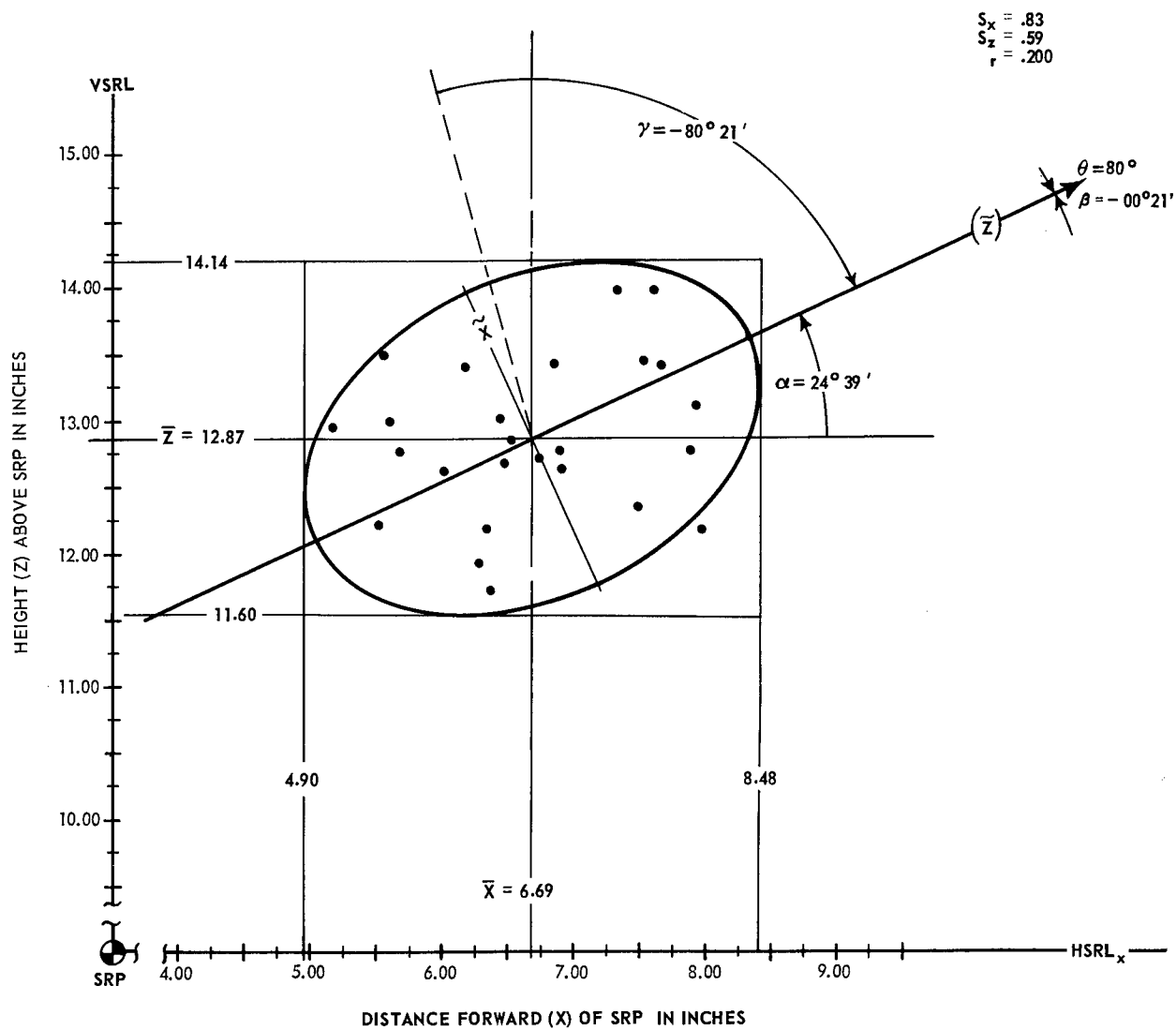


FIGURE 17. CG DISTRIBUTION FOR AN ACCELERATION VECTOR 80° FORWARD OF BACK SUPPORT. 90% CONFIDENCE ELLIPSE SHOWN

center of gravity (as projected onto an xz plane) for all 25 subjects for the acceleration vector simulated.

Since the location of each subject's center of gravity is in this study defined by two normally distributed variables namely, the x and z coordinates, normal bivariate probability ellipses have been calculated (Ref. 8) and drawn in Figures 10 through 17. These probability ellipses represent under the normal bivariate assumptions the 90% confidence limits of the joint distributions of the x and z coordinates of the centers of gravity.

In other words, we are 90% confident that in each figure the center of gravity of an operator's body will fall somewhere within the confines of the 90% probability ellipse shown.

The $\tilde{z}$ line passing through the centroid of each 90% probability ellipse is geometrically its major axis and statistically the reference coordinate of maximum variability of individual centers of gravity about the mean or centroid. Also, its length is proportional to the amplitude of this maximum variability.

The $\tilde{x}$ line of shorter length which also passes through the centroid of each probability ellipse, but perpendicular to $\tilde{z}$, is geometrically the minor axis of the ellipse and statistically the reference coordinate of minimum variability of individual centers of gravity about the mean or centroid. Its length is proportional to the amplitude of minimum variability.

Together, $\tilde{z}$ and $\tilde{x}$ form a coordinate system with origin at the mean or centroid, which is unique to each probability ellipse and in terms of which the distribution in space of individual centers of gravity about their mean is resolved into statistically independent major and minor components respectively. That is, each component is orthogonal (i.e., at 90°) to, and therefore, independent of the other.

The $\tilde{z}$ axis is always parallel to the major component of individual center of gravity variability, and the $\tilde{x}$ axis, conversely, is parallel to the minor component regardless of whether these are parallel to the HSRL_x or VSRL axes. The angle α which $\tilde{z}$ makes with HSRL_x indicates the orientation of the $\tilde{z}$ axis to the HSRL_x - VSRL coordinate system of the body support surface and indicates therefore the inclination or direction of greatest variability in distribution of individual centers of gravity about the ellipse centroid (i.e., mean center of gravity).

The angle γ between seat back support and/or torso and the $\tilde{z}$ axis also indicates the direction of greatest variability, but in terms of the torso long axis and/or seat back support. In this connection the dashed line through the centroid is a parallel to the seat back support and the long axis of the body torso.

In each of the Figures 10 through 17 two sets of tangents to the 90% confidence ellipse have been drawn, one set perpendicular to the HSRL_x, and the other perpendicular to the VSRL.

These two sets of tangents establish in each figure projections of the 90% confidence ellipse on the $HSRL_x$ and VSRL respectively. The limits of each such projection thus represent the 90% confidence limits of individual center of gravity variability about their mean in the x direction (parallel to $HSRL_x$) and in the z direction (parallel to VSRL) simultaneously.

The concept of simultaneous limits is important here. The location with respect to SRP of each plotted individual center of gravity is necessarily characterized as mentioned previously by two variables, its x ($HSRL_x$) and z (VSRL) coordinates. One cannot uniquely describe its location without considering both - simultaneously.

Since each individual center of gravity must be considered as being two variables which are simultaneously established for a given position, the variability of the distribution about their mean (centroid) of all such positions (center of gravity) must be considered as variability in the x ($HSRL_x$) direction and variability in the z (VSRL) direction, simultaneously.

The advantage - nay, necessity - of using the normal bivariate confidence ellipse lies then in this fact, that it represents the simultaneous or - since there is really no need to introduce the concept of time of occurrence here - joint variability of both the x and z coordinates of the distribution of individual centers of gravity about their mean (centroid).

By projecting in the manner shown the "image" as it were of such an ellipse upon the x (HSRL) and z (VSRL) axes we thereby obtain the 90% confidence limits upon $HSRL_x$, while considering the concomitant 90% confidence limits upon VSRL, and the 90% confidence limits upon VSRL while considering the 90% confidence limits upon $HSRL_x$.

It will occur to those who recall their analytic geometry that what we are doing here is merely recognizing the fact that when the $\tilde{z}$ and $\tilde{x}$ axes of the 90% confidence ellipse are tilted with respect to $HSRL_x$ and VSRL the variability of the x coordinates of the centers of gravity is not independent of the corresponding variability of the z coordinates. Thus, so long as the ellipse is tilted, whatever we do in establishing design or confidence limits upon the variability of the x coordinate of centers of gravity will effect the analogous limits established along the z coordinate.

In passing it may be noted here (as it will be more fully discussed later) that when we use instead the $\tilde{z}$ and $\tilde{x}$ coordinate system of each ellipse instead of VSRL and $HSRL_x$ no such interdependence or entanglement of coordinates is encountered.

Also it might be noted that if the $\tilde{z}$ and $\tilde{x}$ axes are parallel with the $HSRL_x$ and VSRL axes (not necessarily respectively) the variability along the x (HSRL) axis corresponds directly with

that along the $\tilde{x}$ (or $\tilde{z}$) axis and is therefore independent of the variability along the z (VSRL) axis, since the latter, in turn, corresponds to the variability along the $\tilde{z}$ (or $\tilde{x}$) axis of the ellipse. If $\alpha = 90^\circ$ or 270° z will correspond with $\tilde{z}$ and x with $\tilde{x}$. If $\alpha = 0^\circ$ or 180° z will correspond with $\tilde{x}$ and x with $\tilde{z}$.

In practical use of the confidence limits shown on the $HSRL_x$ and VSRL in Figures 10 through 17 if we wish to know, say in Figure 10, the limits along the $HSRL_x$ within which 90% of the centers of gravity may be expected to occur for corresponding limits along the VSRL we see these to be 5.23 inches and 7.52 inches forward of SRP - a confidence interval which is 2.29 inches wide.

The confidence interval which corresponds to this on the VSRL has the limits 10.16 inches and 13.13 inches above SRP which establishes an interval 2.97 inches wide.

Thus, the designer can say that for expected physical conditions giving the results shown in Figure 10 he will be at least 90% certain that the expected center of gravity of an individual will lie within the limits given on the $HSRL_x$ and VSRL axes.

In each figure the heavy line with an arrow is the acceleration vector and the angle, θ , it makes with the back support and/or long axis of the torso is given near the head of the arrow.

The included angle between the acceleration vector and the axis $\tilde{z}$ of greatest center of gravity variability is noted as β .

In the upper right-hand corner of each figure are tabulated three important statistical parameters which are commonly used in describing such distribution or "scatters" of data as seen in Figures 10 through 17.

The first two, S_x and S_z , are the standard deviations of the x coordinates and the z coordinates (considered independently) of the centers of gravity. The standard deviation is the universally used "index" of variability of data about their mean or average. Thus, S_x is an index of the variability of the centers of gravity in the x direction (ignoring the concomitant variability in the z direction) about the mean, $\bar{x}$, of the distribution of x coordinates.

Likewise, S_z is the similar index (ignoring concomitant variability in the x direction) of variability of the z coordinates about the mean, $\bar{z}$, of the z coordinates.

The third parameter, r , is the Pearson product moment correlation coefficient, a widely used "index" of the relationship or "covariance" between two normally distributed variables such as the x and z coordinates presented in these figures. It records the degree of closeness with which one variable follows, in changing its numerical values, changes in the numerical values of another

variable. This correlation coefficient may take on any value within the range $-1.00 \leq r \leq 1.00$; 1.00 always implying a perfect or absolutely interdependent relationship, regardless of its sign. A value for r of .00 implies on the other hand, complete independence between two variables, i.e., they do not vary together.

It will be noted that with the exception of the $\theta = 15^\circ$ acceleration vector shown in Figure 10 all of these correlation coefficients were so small numerically as to be, in view of the probability of obtaining different results on other samples of twenty-five subjects, nonsignificant.

Figures 10 through 17 present in detail the raw data which resulted from varying directions of a 1 "g" acceleration vector impinging upon 25 subjects in a stipulated seated body posture.

Figure 18 summarizes these results graphically in terms of the 90% confidence ellipses and their centroids (mean centers of gravity), which were computed on the eight experimental conditions.

The variability apparent in Figure 18 - both that of the centroids and that of the orientation and shape of the ellipses - will be discussed in the following section. Because of the preliminary or exploratory nature of these experiments, the primary purpose of the discussion will be to simplify, if possible, the description of what was observed rather than to "explain" the

phenomena. Consequently, only very brief treatments will be accorded to physiological, anatomical or anthropometrical correlates of these observations.

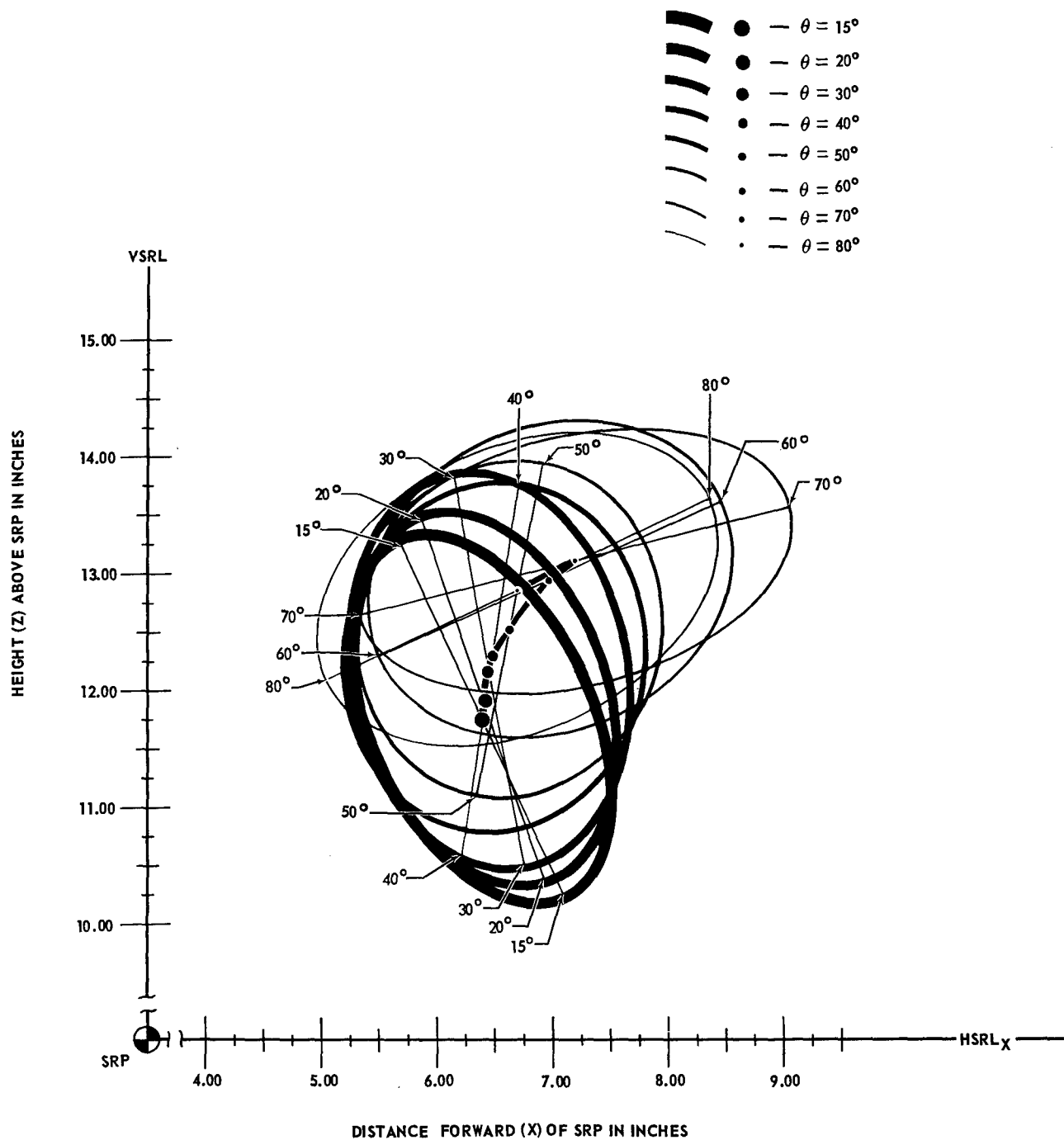


FIGURE 18. CHANGE IN AVERAGE CENTER OF GRAVITY AND ORIENTATION OF DISPERSIONS ABOUT AVERAGES ASSOCIATED WITH CHANGE IN ACCELERATION VECTOR'S DIRECTION RELATIVE TO SEAT BACK (AND TORSO'S LONG AXIS).

DISCUSSION

After examining the collection of eight probability ellipses and their centroids in Figure 18 one thing can be stated without fear of contradiction: there is change! The interesting feature about this change is that it does not seem to be a purely random variability about some hidden average - a wandering back and forth without recognizable pattern. On the contrary, several rather consistent trends occur in the various estimated parameters which we shall use to describe in compact form the observations of centers of gravity.

In Figure 18, and more clearly in Figure 19, we detect for example a consistent change in the location of the centroid (mean center of gravity) of the probability ellipses as the angle θ of the acceleration vector is experimentally increased; e.g., as the direction of acceleration becomes more nearly perpendicular to the torso's long axis the centroid changes its position in a consistent manner.

This change in location takes the form, as Figure 19 shows, of a steady "migration" of the mean center of gravity from an initial position at $\theta = 15^\circ$ of 6.37 inches forward and 11.75 inches above SRP to an extreme position at $\theta = 70^\circ$ of 7.17 inches forward and 13.10 inches above SRP.

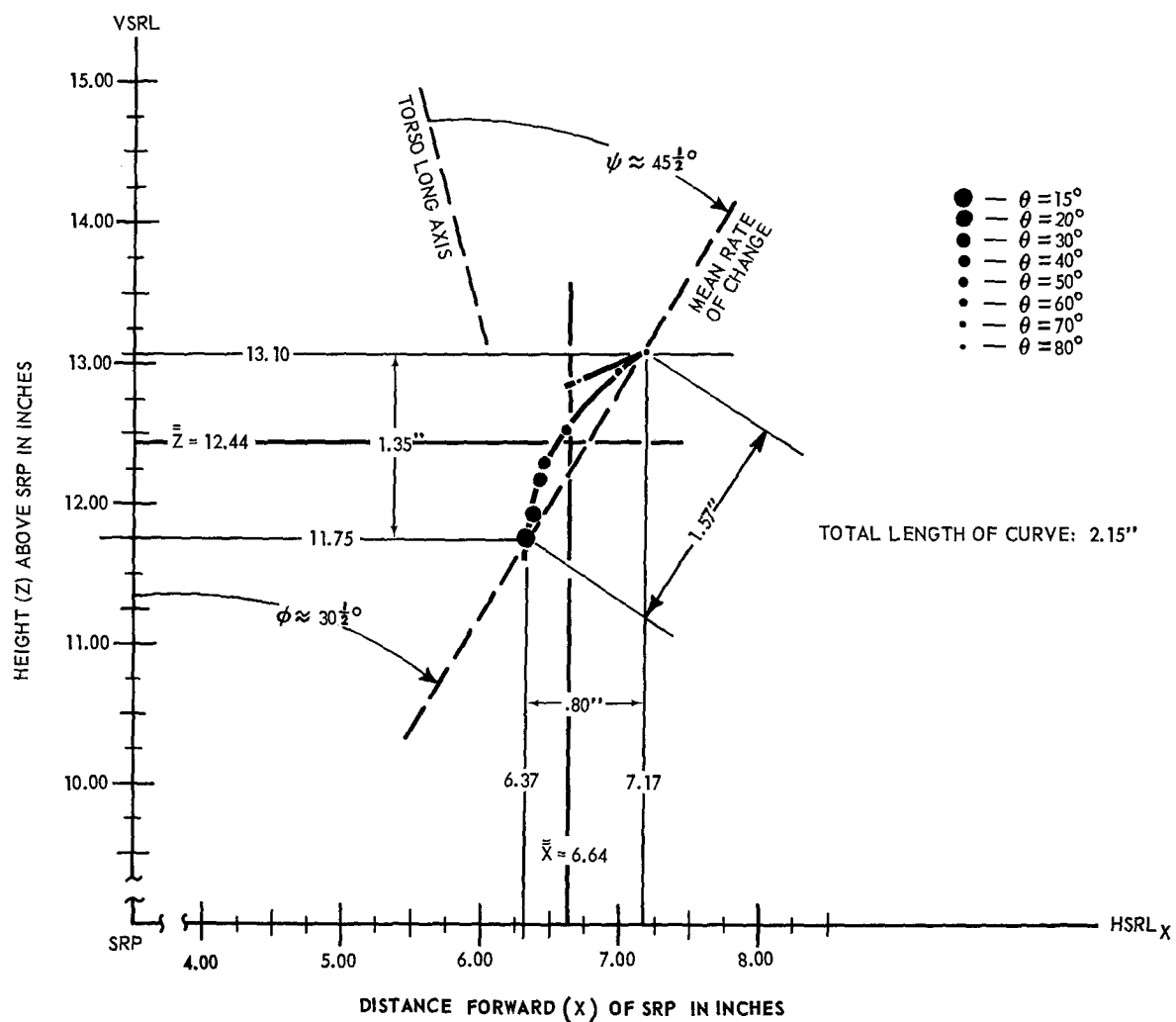


FIGURE 19. CHANGE IN POSITION OF MEAN CENTERS OF GRAVITY (CENTROIDS) AS A FUNCTION OF CHANGE IN DIRECTION (θ) OF ACCELERATION VECTOR

Although it does not move along a linear path, this represents a straight-line distance of 1.57-inch change in the location of the mean center of gravity accompanying only a 55° change in a 1 "g" acceleration vector!

Equally intriguing is the apparent change of this uniform trend which, occurring in the increase of θ from 70° to 80° , produces what appears to be a sudden reversal in the nature of a return of the mean center of gravity to the rear as the acceleration vector attains an angle of 80° forward of the torso.

In regard to this apparent reversal it should be noted that because of the way the legs were positioned by the leg restraint straps (see Figure 1) the axes of the thighs were, on an undetermined number of subjects, parallel with, and the axes of the lower legs (shanks) perpendicular to, the acceleration vector when it moved to an angle greater than 70° .

Such a relationship could conceivably effect the blood volume distribution of the lower extremities to a sufficient extent on a large enough percentage of the subjects to cause a shift toward the back support (and torso axis) of the body center of gravity.

Another interesting aspect of the change in mean centers of gravity with change in direction of the acceleration vector is illustrated in Figure 19. The average rate of change of the mean center of gravity between the position it occupies during the

initial acceleration angle ($\theta = 15^\circ$) and the most forward and highest point to which it moves ($\theta = 70^\circ$) is represented by a line lying at an angle ϕ of approximately $30\frac{1}{2}^\circ$ forward of VSRL.

Since the tangent of $(90-30\frac{1}{2}^\circ)$ is about 1.69 we see that as θ is increased the mean center of gravity moves on an average 1.7 times as far in a direction parallel to the VSRL as it does in a direction parallel to HSRL_x. On the other hand, if in Figure 19 we relate this same range of movement of the mean center of gravity to the long axis of the torso (dashed line) and the thighs (torso and thighs average about 90° to one another) we see that it lies along a line which is about $45\frac{1}{2}^\circ$ (angle ψ) forward of the torso axis.

The tangent of $(90-45\frac{1}{2}^\circ)$ is the average rate of movement of the mean center of gravity with respect to directions parallel to the torso and thighs. This tangent is approximately .98. It follows, therefore, that for a given change in θ , the angle of the acceleration vector, the tendency for center of gravity movement toward the head (i.e., parallel to the torso axis) is on an average from $\theta = 15^\circ$ to $\theta = 70^\circ$ about the same as the tendency for movement to occur at right angles to the torso (i.e., parallel to the thighs).

Regardless of how we choose to reference this migration of the mean center of gravity it is apparent that there is considerable variability in rates of movement about any such "averages" as just discussed.

In Figure 19 the initial movement of the mean center of gravity is greatest in the z (or VSRL) direction. It becomes about equally divided between the z and x (or HSRL_x) directions at acceleration vectors of 40° to 45° and then occurs more and more in the x direction with increasing values of θ .

Even the apparent reversal after $\theta = 70^\circ$ occurs mainly in the x direction. This fact - the phenomenon of movement of the center of gravity forward away from the torso axis generally in the x direction - is the hardest to reconcile with expected shifts in body mass due to blood volume and suspended organ shifts.

Inertial phenomena resulting from the direction of acceleration changing as we changed it would be expected to move fluids and organs headward, but there seems to be no immediately apparent anatomical or physiological correlate with apparent movement of the body center of mass away from the backbone to a point (at $\theta = 70^\circ$) which is actually outside the body!

At the $\theta = 70^\circ$ acceleration vector the mean center of gravity is 10.31 inches forward of the back support surface of the seat as measured perpendicular to it and 10.80 inches above the seat surface. According to Air Force studies (Ref. 1) the average

depth of the abdomen from front to rear is 7.94, measured at the waist and roughly perpendicular to the torso axis on the standing individual.

Further, the same studies on flyers show that the average waist height when sitting is 9.24 above the seat surface, measured roughly parallel with the torso axis.

Assuming arbitrarily that standing waist depth is increased on an average by one-half inch when one sits in the body support we used, it is immediately apparent that the mean center of gravity at the $\theta = 70^\circ$ acceleration vector actually lies on an average about two inches (about 1.9 inches) in front of the belly, and at a height which is on an average just over one and one-half inches above the level of the waist.

We must at present limit comparisons to average body dimensions because there appears to be no relationship (as determined by multiple regression analysis) between either the VSRL or HSRL_x coordinate of an individual's center of gravity and his height and weight, taken either separately or in combination.

We can, however, expect the average (or mean) of one or more variables to coincide with the means of one or more other variables regardless of the degree of mutual relationship between the variables.

Besides these pronounced nonrandom changes in the mean center of gravity, the data in Figure 18 also exhibit other consistencies which have to do with the way individual centers of gravity scatter or distribute themselves about the mean.

This is most easily appreciated by recalling that the 90% confidence ellipses graphically summarize this distribution by varying their orientation with respect to the VSRL and HSRL_x coordinate system as well as their size and shape.

In Figure 18 the major axis of each probability ellipse is shown. Although it is not so easy to verify this in Figure 18, the variability in orientation of these axes (and their associated ellipses) with respect to the VSRL and HSRL_x coordinate system is quite regular.

Remembering that the major axis ($\tilde{z}$ in Figures 10 through 17) of a probability ellipse is the axis along which the greatest amount of variability occurs, the angular orientations of the $\tilde{z}$ axes of the 90% confidence ellipses indicate the direction of greatest variability in the dispersions of individual centers of gravity about their respective means (i.e., the centroids of the confidence ellipses).

In Figure 20 angle γ , the orientations of the $\tilde{z}$ axes of all eight confidence ellipses have been plotted as a function of the angle θ which the acceleration vector makes with the torso (or seat back support).

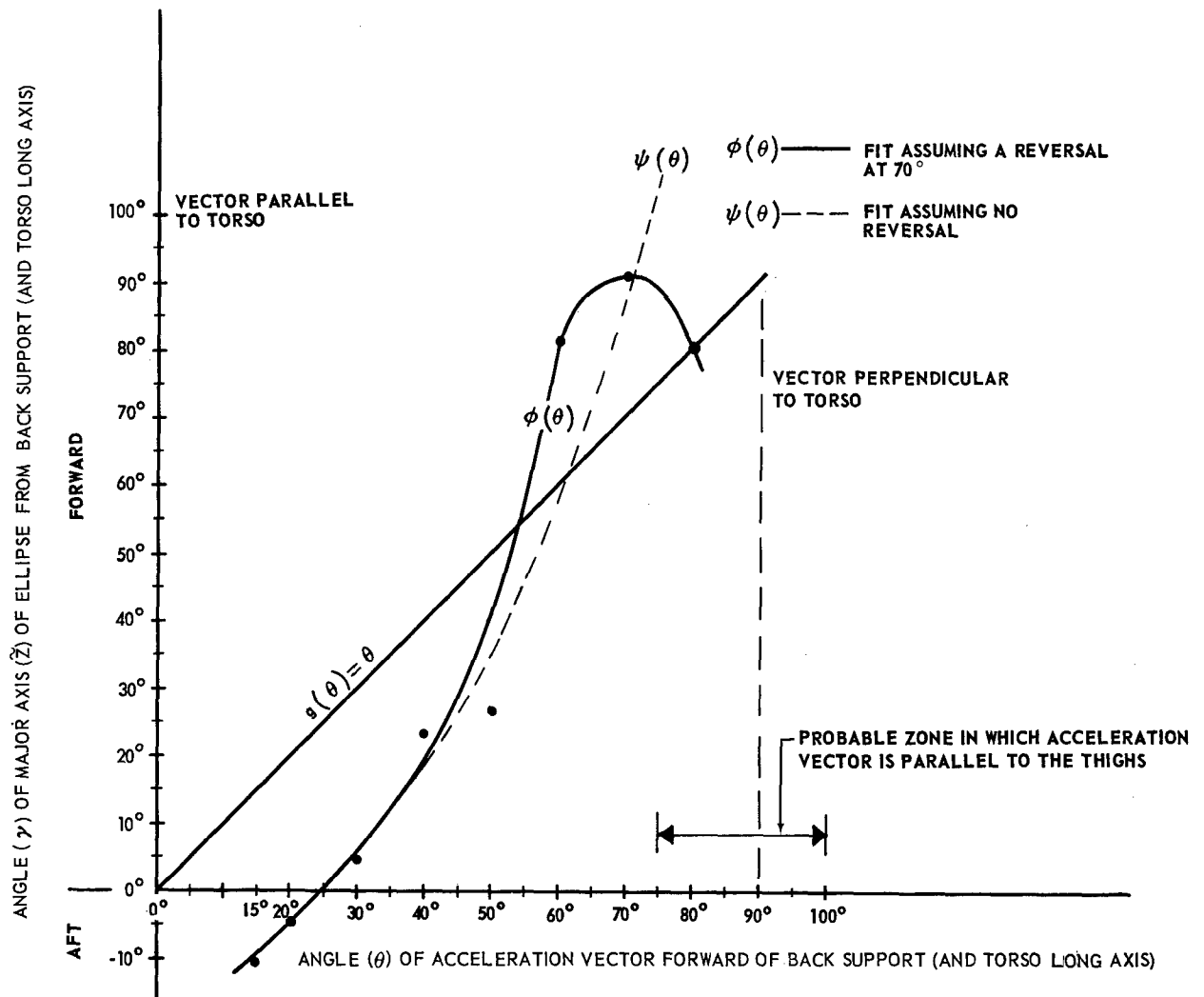


FIGURE 20. CHANGE IN ANGLE (γ) OF ELLIPSE MAJOR AXIS ACCOMPANYING CHANGE IN FORWARD ANGLE (θ) OF ACCELERATION VECTOR. BOTH ANGLES MEASURED FROM SEAT BACK SURFACE.

Here we see more clearly than in Figure 18 the strong relationship which exists between the direction (γ) of greatest variability in individual centers of gravity and the direction (angle θ) of the acceleration vector. In general, this relationship shows that as θ increases so does γ . That is, as the acceleration vector is experimentally rotated forward of the torso's axis the direction of greatest variability in individual centers of gravity likewise rotates forward. Thus, it would appear that changing the direction of acceleration not only affects the position of the average center of gravity for the experimental group but also changes the variability and in a consistent manner. Actually, changing the direction of maximum variability is only one of three ways in which the variability of the individual centers of gravity about the centroids is changed. The other two changes will be discussed presently.

Now since the likelihood of missing any particular man-seat center of gravity by a given amount using a thrust vector which is aimed in a fixed relation to the mean center of gravity of the whole population of man-seat centers of gravity is dependent on both the size and the orientation of the distribution of such centers of gravity, it is worthwhile to consider the changes in orientation of the $\tilde{z}$ axis.

Two curvi-linear functions $\phi(\theta)$ and $\psi(\theta)$ have been fitted by eye to the data plotted in Figure 20. The solid curve, $\phi(\theta)$, assumes the apparent reversal in trend observed between the

$\theta = 70^\circ$ and $\theta = 80^\circ$ acceleration vectors is real. The dashed curve, $\psi(\theta)$, assumes that the observation of γ obtained at $\theta = 80^\circ$ represents merely random variation - such as seen at $\theta = 40^\circ$ and $\theta = 50^\circ$ for example - about a simple continuously increasing function.

An area on the θ axis has been indicated wherein the acceleration vector becomes parallel to the subjects' thighs and perpendicular to the lower leg. It is interesting to note that just as with the reversal in the trend of migration of the mean center of gravity the trend for change in the direction of greatest variability about the mean center of gravity seems to reverse where the acceleration vector approaches this condition of parallelism.

As to which "fit" - reversal $\phi(\theta)$, or increasing function $\psi(\theta)$ - is the "true" one we have insufficient data to decide. It does seem reasonable however to think that the "true" function might lie somewhere between these two in complexity.

In its apparent attempt to follow the experimentally induced angular change in the acceleration vector the $\tilde{z}$ axis of greatest variability does not maintain a constant angular relation to the acceleration vector.

Letting for example β represent this angular relationship in the form

$$\gamma - \theta = \beta ,$$

Figure 21 is a plot of β as a function of γ , the direction of acceleration. We have only to compare the distribution of observed β 's with a hypothetical function, such as the one labeled: $\beta = \text{average } (\gamma - \theta)$, which assumes β is constant, to conclude β is in fact not constant.

The particular hypothetical constant function shown is that for the average observed β , which is $9^{\circ} 07'$ aft of the acceleration vector.

Rather than remaining constant, the angle β tends to vary as some function, f , of the acceleration angle θ , i.e.,

$$\beta = f(\theta).$$

Also, it would appear from Figure 21 that this function is not linear. That is, the change in β with change in θ is not uniform.

Having demonstrated the varying relationship between the direction (γ) of greatest variability of individual centers of gravity and the direction (θ) of the acceleration vector we may examine the two "fitted" functions $\phi(\theta)$ and $\psi(\theta)$ in Figure 20 to see just how they fluctuate as θ changes.

This examination is facilitated by having some simple reference function to compare $\phi(\theta)$ and $\psi(\theta)$ with. Accordingly $g(\theta)$ has been plotted wherein $g(\theta) = \gamma - \theta$, i.e., the angle γ of the axis $\tilde{Z}$ of greatest variability is assumed to not only

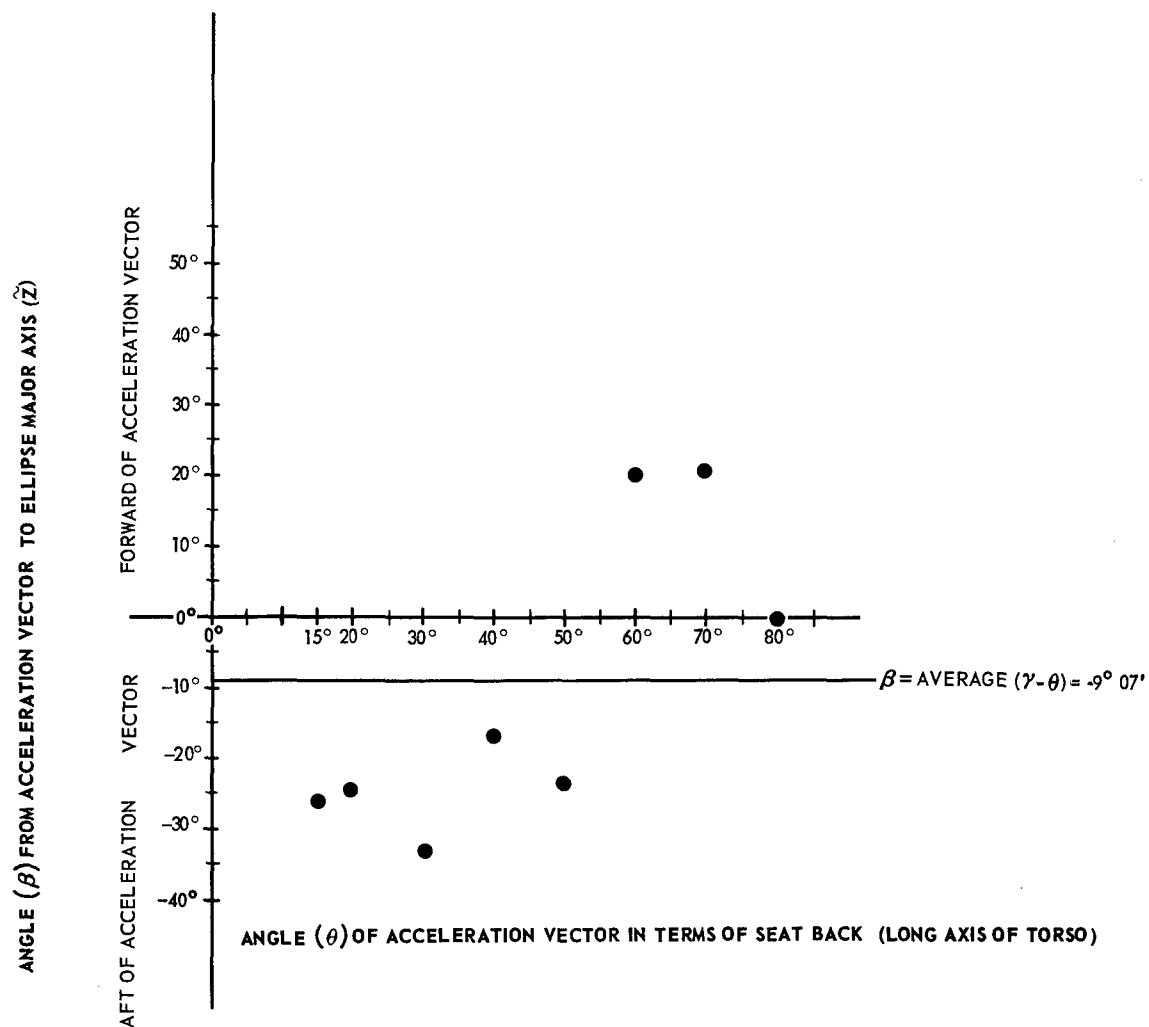


FIGURE 21. COMPARISON OF CHANGE IN ANGLE, (β) BETWEEN ELLIPSE MAJOR AXIS ($\tilde{z}$) AND ACCELERATION VECTOR WITH CHANGE IN ANGLE (θ) OF THE ACCELERATION VECTOR

change at the same rate as θ changes but is also assumed to be equal to θ numerically, for all values of θ tested.

Initially γ tends to lag behind θ . The orientation of the axis of greatest variability tends to maintain a smaller rotation forward of the torso axis than the acceleration vector. The "rate of change" in γ tends to be about equal to the "rate of change" in θ from the initial $\theta = 15^\circ$ condition through about the $\theta = 40^\circ$ condition for both the $\phi(\theta)$ and $\psi(\theta)$ functions.

In this interval, then, the relationship between the axis $\tilde{Z}$ of greatest variability and the acceleration vector remains fairly constant.

Between the $\theta = 40^\circ$ and $\theta = 50^\circ$ acceleration vectors the "rate of change" of γ increases - markedly on the $\phi(\theta)$ curve and less so on the $\psi(\theta)$ curve - and becomes greater than the "rate" at which θ is changing. This is seen as an upswing of the two functions from a course almost parallel to $g(\theta)$, which is the equal "rate of change" function, to a path of ascent which is much steeper than $g(\theta)$.

This increase in rate of change in γ over that of θ reflects the observation that the axis of greatest variability rotates forward rapidly away from the body torso and γ becomes equal to θ at $\theta \approx 55^\circ$ on the $\phi(\theta)$ curve and at $\theta \approx 60^\circ$ on the $\psi(\theta)$ curve.

Thereafter, the rates of change of $\phi(\theta)$ and $\psi(\theta)$, although differing, again become fairly constant: up to about $\theta = 60^\circ$ on the $\phi(\theta)$ curve, and indefinitely so on the $\psi(\theta)$ curve.

Since the "rates" of rotation of the $\tilde{z}$ axis forward of the body torso become and remain as indicated considerably greater than that of the acceleration vector, there is an overshoot so to speak.

Thus, the $\tilde{z}$ axis rotates farther forward of the torso axis than the vector of the acceleration.

If the $\psi(\theta)$ is assumed valid then the axis of greatest variability continues to "overshoot" the acceleration vector by ever increasing amounts as the acceleration vector rotates forward away from the torso axis.

If on the other hand, as seems more likely, the $\phi(\theta)$ curve is genuine - and surely a reversal must indeed occur somewhere if we expect to see the same relationship at $\theta = 375^\circ$ as was observed at $\theta = 15^\circ$ (i.e., after 360° of vector rotation) - then the tendency to overshoot ceases between $\theta = 60^\circ$ and $\theta = 80^\circ$.

Beyond about $\theta = 70^\circ$ a rearward rotation of the $\tilde{z}$ axis is, in fact, apparent. It is of such steadily increasing magnitude that at $\theta = 80^\circ$ the $\tilde{z}$ axis and acceleration vector once again coincide (i.e., $\gamma = 80^\circ 21$).

Of course, in all of this it should be remembered that the $\tilde{x}$ axis or axis of minimum variability of individual centers of

gravity about their mean follows a pattern of change with change in the direction of the acceleration vector which is the exact inverse of that followed by the $\tilde{Z}$ axis.

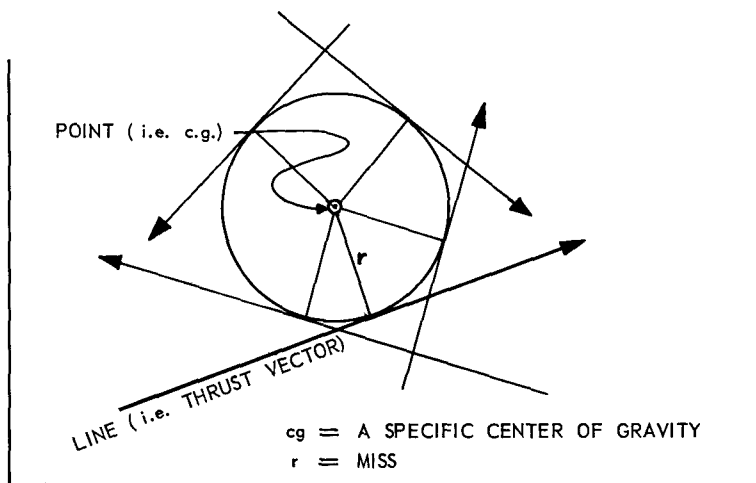
Paradoxically, it is in connection with the $\tilde{x}$ axis of minimum variability about the confidence ellipse centroid that the practical significance of changes in orientation of the $\tilde{Z}$ axis is easiest to see.

For example, consider the basic requirements of all thrust-powered escape devices that the "miss" between the thrust vector and the combined man-device center of gravity always be a minimum. This means that the shortest distance between the position in space of the center of gravity and the line representing the thrust vector should always be minimized for all individuals.

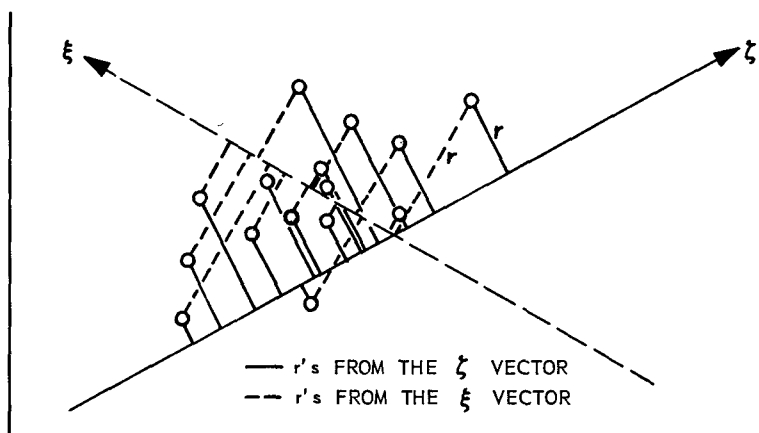
Now the shortest distance between a single point (a given combined center of gravity) and a line (the thrust vector) is a perpendicular to this line passing through the point. As shown in Figure 22A, however, there are an infinite number of these perpendiculars (r) corresponding to an infinite number of possible orientations of the thrust vector which will lie at r distance from a specific center of gravity.

Thus, for just one center of gravity, it is merely necessary to make r as small as possible based solely on engineering considerations in order to minimize the miss between the thrust vector and the center of gravity.

- A. RELATION, r , BETWEEN
A SINGLE CENTER OF
GRAVITY, c.g., AND
THRUST VECTORS



- B. RELATIONS, r 's, OF SEVERAL
CENTERS OF GRAVITY AND
TWO ARBITRARY THRUST
VECTORS



- C. RELATIONS, r 's, OF SAME
CENTERS OF GRAVITY
AND THE VECTOR, z ,
FOR ABSOLUTELY MINIMUM
VARIABILITY

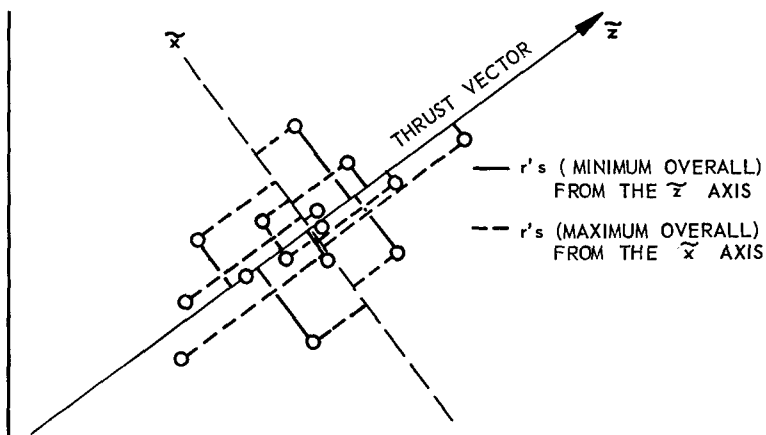


FIGURE 22 RATIONALE FOR MINIMIZING CHANCES OF A MISS BETWEEN
CENTER OF GRAVITY AND THRUST VECTOR

As we know, however, an entire population of individual centers of gravity must be considered. It is quite unlikely that all of these will lie at one point in space. Consequently, we must consider many r 's at once. Figure 22B shows two possible sets of r 's, one set associated with the ξ thrust vector and the other with the ζ thrust vector.

Again, there are an infinite number of such vectors and an infinite number of resulting sets of r 's. But since we are required to minimize for all individuals the distance r we must determine the single (and it can be mathematically shown that there is but one) vector which will absolutely minimize these r 's for the given population.

From statistical and physical laws it can be shown that for a vector of a given orientation to the dispersion of the population of centers of gravity the variability about it will be at a minimum only if it passes through the centroid of the dispersion, which is the mean center of gravity.

Further, for any given population of individual centers of gravity the absolute size of the variability about such a thrust vector will vary as a direct function of the orientation of the vector to the spatial dispersion of the individual centers of gravity which make up the population.

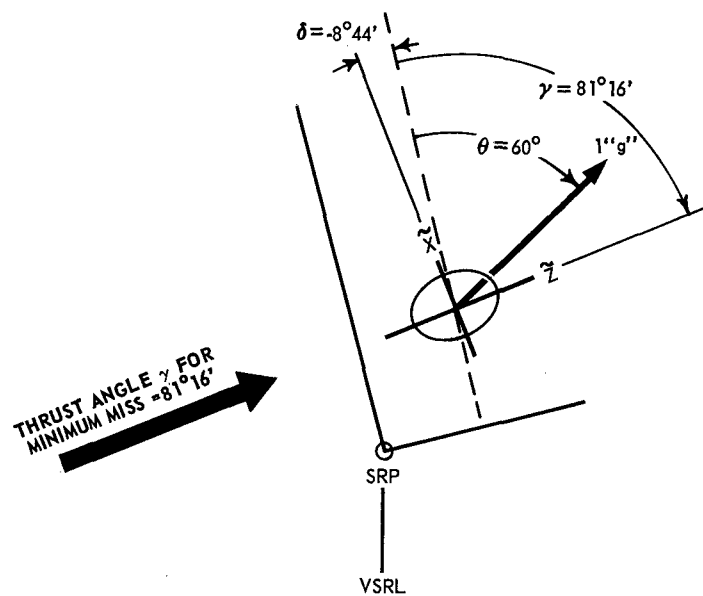
From this and our previous knowledge that the $\tilde{x}$ ellipse axis represents the axis of absolute minimum variability about the centroid (mean center of gravity) it is easy to arrive at the conclusion that the thrust vector's orientation to the total dispersion must be perpendicular to the $\tilde{x}$ axis in order for the variability about the vector to be at an absolute minimum.

Now there is for a given dispersion of centers of gravity but one line which is both perpendicular to the $\tilde{x}$ axis and in addition passes through the mean center of gravity. This is of course the $\tilde{z}$ axis or axis of maximum variability.

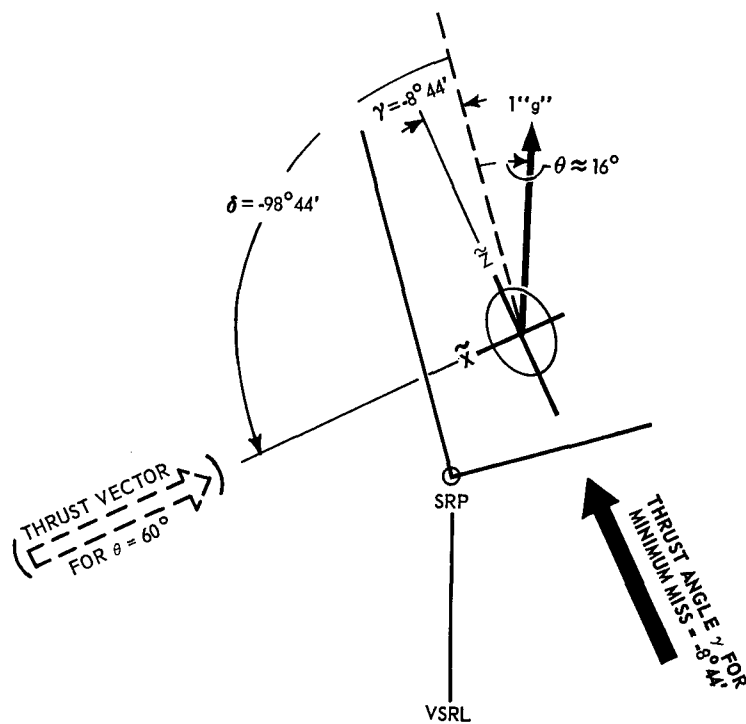
Thus, in order to absolutely minimize the r's and thereby the overall chances of a miss between the rocket thrust vector and the center of gravity we must, as shown in Figure 22C, aim the rocket so that its thrust line coincides with the $\tilde{z}$ axis.

In the light of these conclusions the significance of the $\tilde{z}$ axis should now be apparent. The discovery that this axis of greatest variability changes its orientation markedly relative to the human occupant of a simulated escape system begins now to assume an aspect of practical as well as theoretical importance.

In Figure 23A, for example, it may be seen that when the vector of 1 "g" acceleration is 60° forward of the escape system occupant's torso ($\theta = 60^\circ$) the $\tilde{x}$ axis of minimum individual center of gravity variability forms an angle, S , which is $8^\circ 44'$ aft of the torso. A perpendicular to this axis that also passes through



A. ANGLE OF THRUST REQUIRED FOR A MINIMUM MISS AT $\theta = 60^{\circ}$



B. ANGLE OF THRUST FOR MINIMUM MISS AT $\theta = 16^{\circ}$

FIGURE 23 COMPARISON OF THE ANGLES (γ) OF THRUST WHICH YIELD MINIMUM MISS OF INDIVIDUAL CENTERS OF GRAVITY. NOTE: γ (IN A) - γ (IN B) = 90°

the ellipse centroid is, as mentioned, the $\tilde{z}$ or greatest variability axis, which lies at an angle, γ , of $81^{\circ}46'$ forward of the occupant's torso (and seat back support).

Accordingly, in order to minimize overall the miss between the thrust vector of a fixed rocket and individual centers of gravity, the thrust vector must be aimed at an angle of $81^{\circ}46'$ forward of the torso and seat back support.

In Figure 23B on the other hand, it is apparent that with a one "g" acceleration vector which is approximately (interpolated from $\phi(\theta)$ of Figure 20) 16° forward of the torso and seat back support, the $\tilde{x}$ axis of minimum variability forms an angle, γ , of $98^{\circ}44'$ aft of the torso axis— 90° (i.e., $\gamma_A - \gamma_B = 90^{\circ}$) further to the rear than with the $\theta = 60^{\circ}$ acceleration vector.

The entire confidence ellipse of the distribution of individual centers of gravity about the mean or centroid has thus rotated 90° to the rear as a result of rotating the acceleration vector 44° rearward toward the torso axis. Accordingly we see that the $\tilde{z}$ axis now forms an angle, γ , of $8^{\circ}44'$ to the rear of the torso axis and seat back support.

At an acceleration vector of $\theta = 16^{\circ}$ then, the thrust vector angle necessary to achieve a minimum miss, overall, between it and individual centers of gravity is $8^{\circ}44'$ aft of the torso axis and seat back support.

Thus, in order to absolutely minimize the "miss" for both the $\theta = 60^\circ$ and $\theta = 16^\circ$ acceleration vectors, the thrust vector must be rotated on its mounting 90° !

Actually, if we assume that $\phi(\theta)$ of Figure 20 describes the required changes in orientation (γ) of the rocket thrust vector in order to minimize the "miss" equally well for any θ tested it appears that the rocket must swivel in its mountings. That is, for an acceleration vector of one "g" amplitude ranging in its direction from 15° through 80° forward of the torso axis, we must be able to rotate the rocket in its mounting from $10^\circ 53'$ aft of the torso and seat back support to $91^\circ 16'$ forward of the torso - or through an angle of at least $102^\circ 19'$!

But that is not all. Such rotation merely accommodates the change in the orientation of the $\tilde{z}$ axis. We must remember that there is also a decided change in the spatial location of the centroid through which we must aim. This amounts to a range of about one and one-eighth inches of movement toward the head and toward the knees or, in terms of the standard reference axes, 1.35 inches parallel to VSRL and .80 inch parallel to HSRL_x.

The rocket thrust vector should, therefore, not only change its orientation in accordance with the direction of acceleration but it should pursue the mean center of gravity as the latter moves along a path in space similar to that shown in Figure 19.

If in addition to the basic requirement for miss minimization given above in the general discussion of escape systems, it is further stipulated that not only must the "miss" of individual centers of gravity be minimized overall but that in any case the miss shall not exceed numerically a given amount - say e inches - then another aspect of individual variability about the confidence ellipse centroids must be considered.

This second feature of individual variability about the centroid concerns the amplitude of the minimum and maximum variabilities along the respective $\tilde{x}$ and $\tilde{z}$ axes of the confidence ellipse.

Earlier, in the explanation of Figures 10 through 17, it was noted that the length of the $\tilde{z}$ and $\tilde{x}$ axes of the confidence ellipses is proportional to the amount of individual variability, in these respective directions, about the mean or centroid. And since we have been dealing exclusively with 90% confidence ellipses these axes are, therefore, proportional to 90% of the expected individual variability along the respective axes - 45% on either side of the mean.

If we had used 50% confidence ellipses the axes would have been proportional in their length to 50% of the expected individual deviations in centers of gravity from the mean. If we had used 99% confidence ellipses the axes would be proportional in their respective lengths to 99% of the variability, and so forth.

In the explanation of Figures 10 through 17 the concept was presented of summarizing for each acceleration vector the total individual variability as measured along the VSRL and HSRL_x axes by using statistical indices S_x and S_z (called standard deviations) of this variability. In a like manner, the variability in terms of the $\tilde{z}$ and $\tilde{x}$ axes may also be conveniently summarized.

Thus, we have for each observed distribution of individual centers of gravity a standard deviation S_z' , which is the statistical index of variability along the $\tilde{z}$ axis, and a standard deviation S_x' , which is the index of variability along the $\tilde{x}$ axis.

In the following discussion it should also be remembered that S_z' is completely independent of S_x' . That is, the deviation which an individual's center of gravity makes from the centroid along the $\tilde{z}$ axis is in no way affected by or dependent upon the deviation of the same individual's center of gravity from the centroid in the $\tilde{x}$ direction.

Now the proportional relationship between the length of the $\tilde{z}$ and $\tilde{x}$ axes on the one hand and the S_z' and S_x' standard deviations on the other is:

$$M = \pm A_p S_z' \quad 1.$$

$$L = \pm A_p S_x' \quad 2.$$

$$\text{NOTE: } A_p = \sqrt{\chi^2}, \text{ df} = 2$$

where M stands for the length on either side of the centroid of the

$\tilde{z}$ axis, L represents the length of the $\tilde{x}$ axis on either side of the centroid and A represents a statistical constant χ_p^2 (called "Chi-square"), which is selected from widely available tables (Ref. 8) according to p , the desired level of confidence and a value of 2 for "degrees of freedom."

Thus, we see that the length, M , of the $\tilde{z}$ axis on either side of the centroid is in the proportion of A_p to $S_{z'}$, the standard deviation along the $\tilde{z}$ axis; and the length, L , of the $\tilde{x}$ axis on either side of the centroid is in the proportion of A_p to $S_{x'}$, the standard deviation along the $\tilde{x}$ axis.

That is:

$$\pm \frac{M}{S_{z'}} = A_p, \quad 3.$$

$$\pm \frac{L}{S_{x'}} = A_p. \quad 4.$$

If, therefore, it is required to know what are the chances of a thrust vector-center of gravity miss being greater than the allowed e inches where the thrust vector is aimed so as to obtain overall the least possible miss, we substitute e for L in equation (4) and solve for A_p .

Since it is p that we wish known namely, the probability, we look for a value equal to $A(=\chi^2, df=2)$, in a Chi-square probability table. It will be found in association with a given p which is taken as the probability of e exceeding the allowed value.

This example illustrates, at the cost of delving to a slight degree into the mechanics of statistics, in a very real and practical sense how the size of $S_{x'}$, the index of individual center of gravity variability about the mean, should be of considerable importance in making decisions regarding the design of thrust powered escape systems.

Quite obviously from equation (4) the probability, p , of a miss using such a thrust vector is dependent both upon the distance e and the amplitude of $S_{x'}$. If e is given then the likelihood of a miss becomes a direct function of $S_{x'}$, the variability along the $\tilde{x}$ axis.

If we cannot use a thrust vector which passes through the mean center of gravity or which can not always be parallel to the $\tilde{z}$ axis, the probability of a miss, although involving somewhat more complicated relationships than considered here, will nevertheless be a function of $S_{x'}$ and $S_{z'}$.

It will be of some practical interest then to observe that as the angle, θ , of the acceleration vector changes so also do changes occur in the amplitude of $S_{x'}$ - and also of $S_{z'}$. These changes are plotted in Figure 24A where the amplitudes of $S_{z'}$ are connected by a dashed line and those of $S_{x'}$ are connected by a solid line.

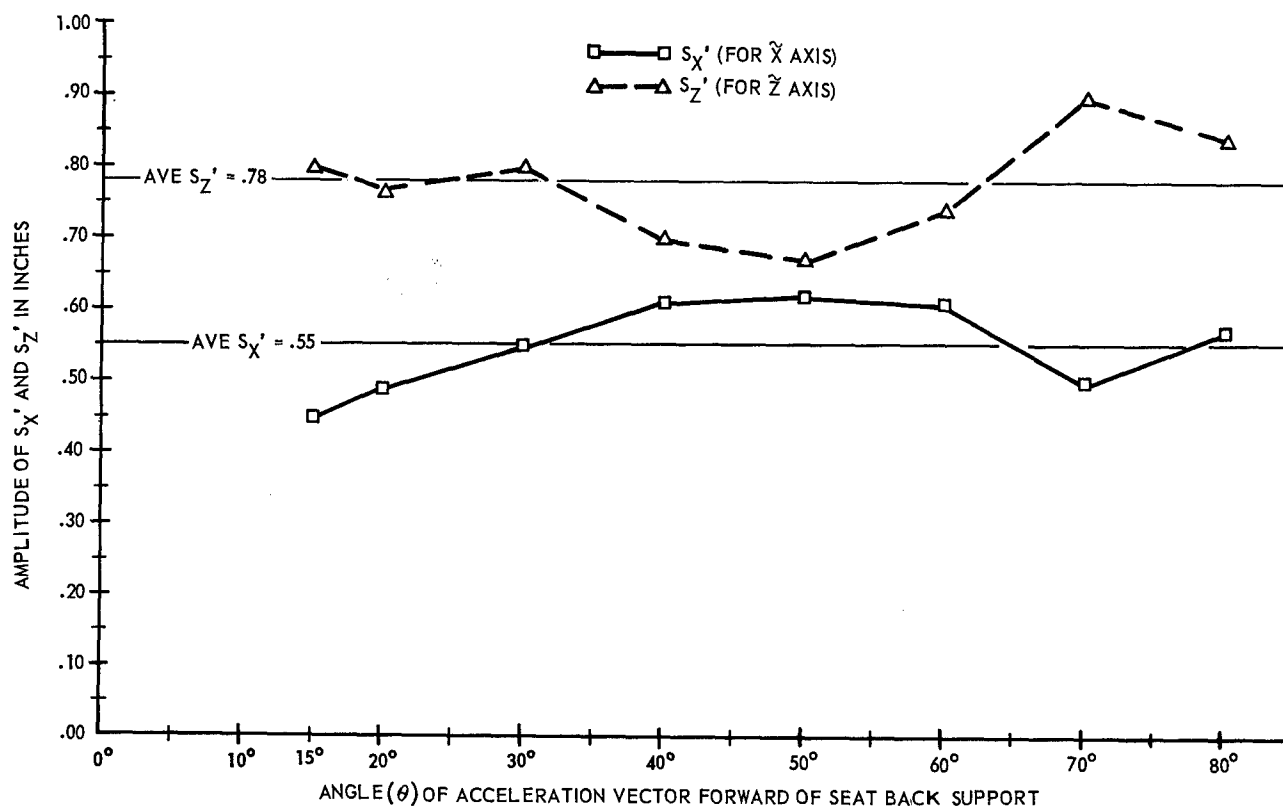


FIGURE 24A. RELATIONSHIP BETWEEN THE STANDARD DEVIATIONS $S_{X'}$ AND $S_{Z'}$ ALONG THE $\tilde{X}$ AND $\tilde{Z}$ AXES RESPECTIVELY OF INDIVIDUAL CENTERS OF GRAVITY FOR VARYING DIRECTIONS (θ) OF ACCELERATION

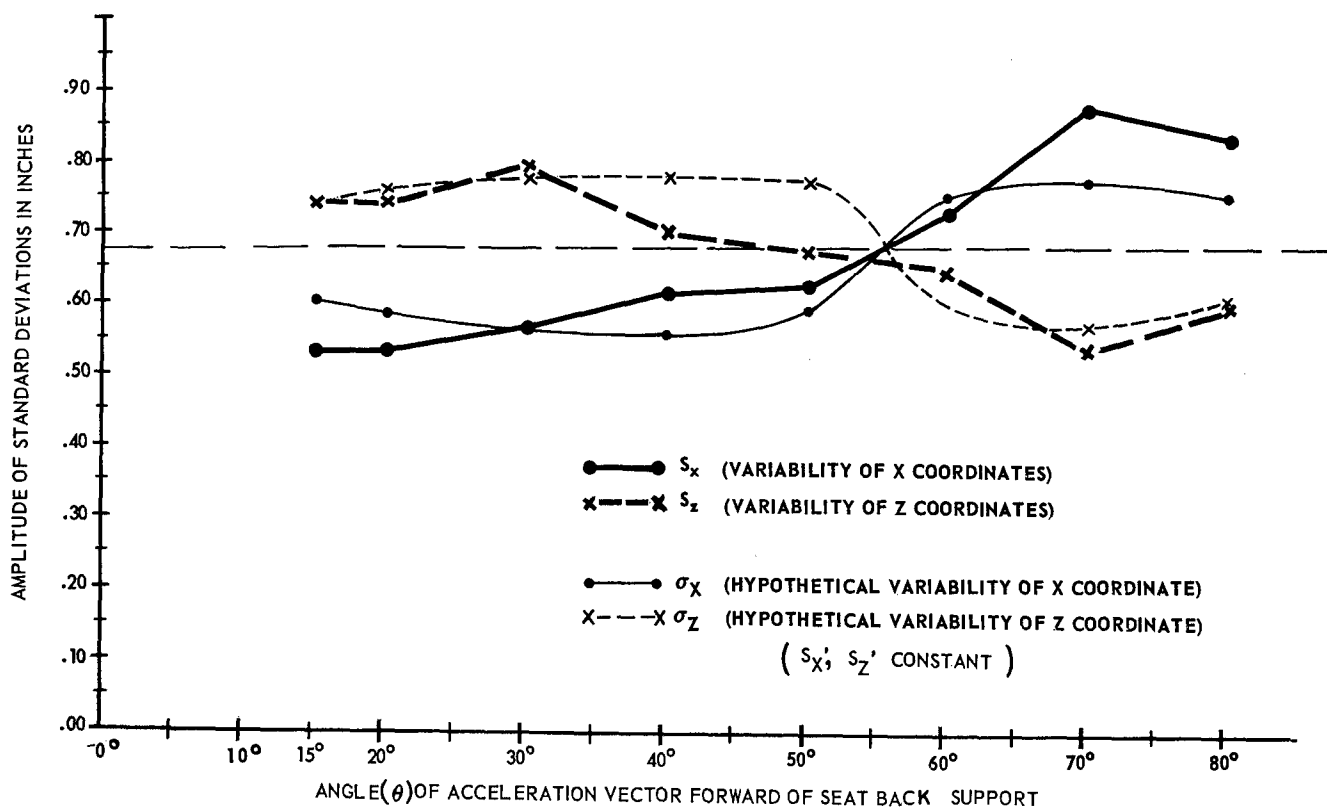


FIGURE 24B. RELATIONSHIP BETWEEN VARIABILITY (STANDARD DEVIATIONS) OF X AND Z COORDINATES OF SUBJECT'S CENTERS OF GRAVITY FOR VARYING DIRECTIONS OF ACCELERATION

Once again a pattern may be seen which suggests that the observed changes are not purely random. Initially, at $\theta = 15^\circ$, $S_{x'}$ is only 56% the size of $S_{z'}$. As θ increases however, $S_{x'}$ increases and $S_{z'}$ decreases both at about the same rate so that when $\theta = 50^\circ$, $S_{x'}$ is up to 92.5% the size of $S_{z'}$. At about $\theta = 50^\circ$ then, there seems to be a tendency for $S_{x'}$ and $S_{z'}$ to converge.

Beyond $\theta = 50^\circ$ however, the two variabilities diverge more and more until at $\theta = 70^\circ$, $S_{x'}$ is only 56% of $S_{z'}$. But at this point an interesting thing occurs. The divergent trend halts and as θ reaches 80° the two variabilities seem to be once again converging so that at $\theta = 80^\circ$, $S_{x'}$ has returned to 68% of $S_{z'}$.

This reversal in trend occurring between $\theta = 70^\circ$ and $\theta = 80^\circ$ would seem to correspond with such reversals already noted in both the trend of the movement of mean centers of gravity (centroids) and of the forward rotation of the $\tilde{z}$ axis of greatest variability about the centroid.

Interestingly enough, in Figure 24A the change in $S_{x'}$ seems to be virtually a mirror image of the change in $S_{z'}$. This suggests at first that $S_{x'}$ is related to $S_{z'}$. This, nevertheless, is not the case because of the basic definition of a bivariate confidence ellipse. In fact if $S_{z'}$ is plotted as a function of $S_{x'}$, with the effects of θ removed from both a scatter of points results which is entirely lacking in consistency or recognizable trend.

Thus, the apparent relationship between the minimum variability, $S_{x'}$ and $S_{z'}$, the maximum variability about the centroids,

is the purely fortuitous result of each type of variability independently following its own unique relationship with θ , the acceleration vector angle.

In comparing these respective relationships it would seem that the effect of θ upon S_x , is about the same in an absolute sense as the effect of θ upon S_z . Mostly, it is the signs of the changes (i.e., increasing or decreasing) which differ. In general these changes are of opposite sign.

Figure 24A also indicates that by orienting the rocket thrust vector normal to the $\tilde{x}$ axis, which is the direction of the variability which S_x measures, we would considerably reduce the overall chances of a "miss" of a given distance between $\theta = 15^\circ$ and $\theta = 40^\circ$ and between $\theta = 60^\circ$ and $\theta = 80^\circ$, but in the central area of the figure between $\theta = 40^\circ$ and $\theta = 60^\circ$ this reduction, while still marked, would not be nearly so great.

Since VSRL and HSRL_x are very useful as well as standard reference coordinates for designing escape systems (Refs. 6 and 7), it is interesting to see the effect of the variability in the sizes and orientations of S_x and S_z as they are projected upon the VSRL and HSRL_x coordinate axes.

In other words, it will be instructive to observe a third type of variability, the distribution of individual centers of gravity in terms of their x (parallel to HSRL_x) and z (parallel to VSRL) coordinates. The measures of variability along the x and z coordinates are the standard deviations, S_x and S_z , described previously in connection with Figures 10 through 17.

Figure 24B presents these effects. From $\theta = 15^\circ$ through $\theta = 50^\circ$ the relationship between (heavy solid line) S_X and S_Z (heavy dashed line) is quite like that of $S_{X'}$ to $S_{Z'}$. Between $\theta = 50^\circ$ and $\theta = 60^\circ$, however, S_X becomes equal to S_Z . Thereafter, S_X gets larger and larger while S_Z becomes smaller and smaller.

As with the $S_{X'}$ and $S_{Z'}$ relationship, however, a reversal in the respective trends of S_X and S_Z occurs between $\theta = 70^\circ$ and $\theta = 80^\circ$.

The principal difference between the relationship of S_X to S_Z and that of $S_{X'}$ to $S_{Z'}$ is the "crossing over" which occurs between $\theta = 50^\circ$ and $\theta = 60^\circ$, that is, the phenomenon of S_X becoming larger than S_Z .

This "crossing over" is a phenomenon due entirely to the forward rotation (i.e., increasing γ) of the $\tilde{z}$ axis of greatest variability and the resulting change in the angles of projection of the combined minimum and maximum variability upon the VSRL and HSRL_x axes respectively.

Specifically, it can be shown through a manipulation of known relationships (Ref. 8, p. 597) that the standard deviations of the distribution of individual centers of gravity along such axes as HSRL and VSRL bear the following relationships to the standard deviations of this same variability as measured along the $\tilde{x}$ and $\tilde{z}$ axes:

$$S_x = \sqrt{\cos^2 \alpha S_z^2 + \sin^2 \alpha S_x^2} \quad 5.$$

$$S_z = \sqrt{\sin^2 \alpha S_z^2 + \cos^2 \alpha S_x^2} \quad , \quad 6.$$

where angle α is the angle shown in Figures 10 through 17 measuring the inclination of the $\tilde{z}$ axis to $HSRL_x$.

This being so, it is readily apparent that if $S_x \neq S_z$, both S_x and S_z will change as α changes even if S_x and S_z remain constant.

This is demonstrated in Figure 24B, wherein curves have been plotted for constant values of S_x and S_z . The values chosen were the averages, .55 for S_x , and .78 for S_z . The α 's chosen were the ones observed to accompany the values of θ as shown in Figures 10 through 17.

The hypothetical pair of functions shown for σ_x (light solid line) and σ_z (light dashed line) bears a close resemblance to the plot of the observed values of S_x and S_z . The hypothetical crossover occurs, as expected, at an angle α of 45° , which according to Figure 20 would be expected at an acceleration vector angle between 51° and 61° depending upon whether $\phi(\theta)$ or $\psi(\theta)$ is used.

Of course, other hypothetical constant values for S_x and S_z , taken from those observed would change the hypothetical functions shown in Figure 24B, but not appreciably.

The only reason that this set of hypothetical functions does not correspond exactly with the observed plots in Figure 24B is that S_x and S_z do not, as is shown in Figure 24A, remain constant, but vary instead.

Thus, the discrepancy between the hypothetical "expected" values σ_x and σ_z , assuming S_x and S_z constant, but not equal, and the S_x and S_z values actually obtained represents the unique contribution to the final outcome of S_x and S_z of the variability in S_x and S_z .

SUMMARY AND CONCLUSIONS

If the results of our experimental manipulation of the direction in which seated human subjects accelerate at one "g" are acceptable as evidence of real, rather than merely apparent, phenomena, it may be concluded that the position of the human center of gravity is strongly affected by changes in the direction of low amplitude acceleration.

In varying such an acceleration vector from an almost rump-to-head direction (i.e., from a vector oriented 15° forward of the torso axis) to an almost back-to-belly (to an angle of 80° forward of the torso axis) effects are produced upon the individual centers of gravity of twenty-five male test subjects which are large as well as consistent.

On an average, a rotation of a one "g" acceleration vector through an angle of 65° is accompanied by a migration of the human center of gravity along a curved path of about 2.15 inches in arc length.

On an average, this migration runs in a direction from tail bone (coccyx) to belly-button (umbilicus) with the distance moved along a rump-to-head axis being about equal to the distance moved along a rump-to-knee axis.

In particular, however, the direction of migration varies markedly from this average, being initially more pronounced in the rump-to-head direction but later, as the direction of

acceleration becomes more nearly perpendicular to the torso, more pronounced in the rump-to-knee direction.

The sensitivity of the migration of the average center of gravity to changes in direction of the acceleration vector is acute.. It is possible, in fact, to fit by eye a curve to this relationship from which actually observed points deviate by a rather small amount.

Accompanying the migration of average centers of gravity is a consistent change in the distribution or variability of individual centers of gravity about these averages.

Initially at a 15° acceleration vector, the greatest portion of this variability lies along a line about 11° aft of the torso axis. As the direction of acceleration is rotated forward away from the torso the direction of greatest variability likewise rotates forward slowly at first and then more rapidly until it coincides with the acceleration vector when the latter is between 50° and 60° forward of the torso axis.

Beyond this angle individual variability about the average becomes more and more nearly perpendicular to the torso axis - more so, in fact, than the experimentally induced changes in the direction of acceleration.

When the angle of the acceleration vector becomes greater than 70° forward of the torso's axis, the individual variation about the mean center of gravity suddenly changes. The trend of this variability to accompany the acceleration vector by rotating forward quickly reverses, and at an acceleration vector of 80° forward of the torso axis the trend in direction of individual variability seems well on its way back to the rear toward the rump-to-head axis.

Not only does the direction of this individual variability thus change in accompaniment to forward rotation of the acceleration vector but its absolute size does also, although in accordance with a different relationship to the direction of acceleration.

Several practical conclusions can be drawn from these phenomena. One concerns the implications for tests which are to be done to determine for a specific escape system the operator-system center of gravity.

The implications are simply these: Since such tests will undoubtedly be conducted under the one "g" pull of gravity - i.e., in a one "g" acceleration field - and since, as we have seen, the location of the average center of gravity can move at least two inches in a consistent pattern which is apparently dictated by the direction of the one "g" acceleration vector, it behooves the experimenter to give careful consideration to the orientation of his subjects and seat to the gravitational vector when centers of gravity are to be determined.

Several (Refs. 3, 4, and 5) such determinations have been accomplished by various workers and undoubtedly more will be in the future. The "suspension method" is the method most frequently used. It is an excellent method. Unfortunately, however, little consistency is found in the selection of angles, with respect to gravity, at which the plumb lines will be observed passing through the center of gravity.

As a matter of fact, there is a tendency to deliberately take the successive readings of the plumb lines at mass suspension angles which differ by amounts often in excess of twenty to thirty degrees.

Such practice in view of the difficulty in obtaining truly "frictionless" bearings may, indeed, lead to greater accuracy in determining the plumb line intersections and, thereby, the center of gravity of a perfectly rigid body but when testing the human body lead, instead, to results of extremely inaccurate nature.

Such practice in the case of human subjects will, since their centers of gravity are different with each suspension angle, lead to results which have by no means the same meaning as would similar operations on a rigid body. Using human subjects in such a manner actually yields - if, say, three widely spaced suspension angles were used - three different indeterminate assessments of three quite different centers of gravity.

Nor does it necessarily follow that the plumb line intersections so obtained even indicate an "average" (in the usual sense of the term) location of the subject's center of gravity as it admittedly moves during the determinations. The nature of this movement is such that a claim to be an arithmetical average for such a determination may be completely erroneous. It may actually be, because of the strange path of migration, a geometric or harmonic average, or an even more exotic brand.

The point is that such methods are fraught with difficulties of interpretations. We can only approximate a knowledge of the exact location of the human center of gravity using such test methods as are now available.

The discrepancy between where we think the center of gravity of the human body is and where it really is may, in the case of the suspension method, be made smaller and smaller by choosing suspension angles closer and closer together. Obviously, the limit of this process will be reached (i.e., the discrepancy will be zero) only when the difference between successive angles is zero - an impractical condition.

It would seem, therefore, that if accurate determination of the human center of gravity is essential one should attempt to keep differences in successive mass suspension angles as small as possible even at the expense of considerable sophistication of experimental technique and apparatus.

In any case, the least that an investigator should do is to accurately determine the angles which the one "g" gravitational acceleration vector makes with the subjects' anatomy during the suspension measurements. If this type of essential information continues to be unavailable, hopes of obtaining comparable results from different investigations must be based largely on fortuitous occurrences, rather than predictable ones - a discouraging prospect.

Since considerable attention has been given it in the Discussion, only a brief recapitulation need be made here of another practical aspect of these results - an aspect which could well assume the proportion of being a life or death matter for an ejected aircraft operator. This is, of course, the matter of aiming the rocket thrust vector correctly.

In any rocket-powered escape system the rocket will be either adjustable or it will be fixed. If it is adjustable its range of adjustment will be within some finite fixed limits. The adjustment will either be made manually or automatically. The adjustment will be in accordance either with decisions made by the human operator (or designer) or by automatic inputs reflecting physical status, which in turn can have any number of parameters, ranging from the height at which the operator has adjusted his seat to the amplitude and direction of the ambient acceleration vector at the time of escape systems actuation.

Regardless of whether the rocket is fixed or adjustable there will always be the problem of the likelihood of its thrust vector missing an individual's center of gravity (or the combined escape system and individual center of gravity) by an amount greater than that which other design features (such as aerodynamic surfaces) can compensate for to prevent dangerous spinning or fatal changes in the trajectory of the ejected mass.

This likelihood is, as has been described, a function of the size and orientation of the cluster of individual centers of gravity about the average in the total population. If the rocket thrust is absolutely fixed, and therefore aimed in some invariant relationship to this average center of gravity, it follows from the laws of probability that the likelihood of a "miss" of unspecified distance between rocket thrust and a given individual's center of gravity is infinitely great, regardless of the size and orientation of the distribution of individual centers of gravity about their average.

On the other hand, the likelihood of a miss of distance greater than some specified maximum, say e inches, is a finite and predictable quantity, but dependent in its value upon the size and orientation of the dispersion of individual centers of gravity about the rocket thrust vector.

Now it also follows from the laws of probability that this dispersion in any given single direction is minimum about the average, or mean center of gravity. Accordingly, it follows that, in general, the likelihood of a miss in excess of e occurring is least if the rocket thrust vector is aimed directly at the average center of gravity.

But since the average center of gravity moves in response to changing directions (and probably in response to changing amplitudes also) of accelerations, this requires that the rocket thrust be able to "track," as it were, the average center of gravity as it migrates.

This is not all, however. In the case of centers of gravity we are concerned with dispersion in more than a single direction - three actually, although it was possible to investigate only two in this study.

Again, from the laws of probability, we know that in the case of dispersions in multiple directions there is a single axis which is the direction of least variability. This corresponds in the two-dimensional distribution studies with the $\tilde{x}$ axis of the two-dimensional probability ellipse, which has been described in detail.

Thus, if the likelihood of a miss greater than e is to be minimized - if we are to play the odds - not only should the rocket thrust always pass through the average center of gravity, but it should do so in a direction perpendicular to this axis of minimum variability.

Our experiments have revealed, however, that this axis changed considerably in its orientation to the human body, but in a predictable manner which is a function of the direction in which the acceleration is acting on the body.

Thus, in order for the designer to absolutely minimize the chance of undesirable, perhaps, even fatal, consequences due to "missing" the center of gravity, he must provide a rocket installation which can track the average center of gravity, but in a manner which will maintain the proper orientation of the thrust vector to the minor axis of the expected dispersion of individual centers of gravity.

And even this is not all! Even when the thrust vector passes through the average center of gravity and in the proper orientation to the axes of dispersion about this center there still remains the problem of variability (again as a function of the direction of acceleration) of these axes in their absolute size.

Thus, even when stringently meeting all other requirements the designer will be faced with the fact that as the ambient acceleration vector changes in direction so will the absolute size of the minimum dispersion and, therefore, so will the risk of obtaining an individual center of gravity which lies farther than the allowable e inches from the tracking rocket thrust vector.

We may, however, take encouragement from the fact that this last source of variability contributes much less to the total variability in the likelihood of exceeding e than that contributed by the changing orientation of the axis of minimum variability or the migration of the average centers of gravity. Exactly how much less is difficult to calculate at present due to the uniqueness of the mathematical model of the probabilities involved. A rash estimate, however, might make it out to be contributing to only some 30% of the total variability in individual centers of gravity.

Also, as a very rough indicator of what could be accomplished by compensating movement of the rocket thrust vector, the rectangular area which encloses about 90% of all observed individual centers of gravity at all angles of acceleration vector tested is twice as large in area as that which will enclose approximately 90% of the same centers of gravity after the effects of migration of the average centers of gravity and the effects of the rotation of the axes of dispersion are eliminated.

Finally, and in conclusion of the Conclusions, it is recognized that the requirements for minimum miss outlined above may not be compatible with other more urgent requirements in escape system design, namely those of just getting the man clear of the aircraft regardless of subsequent events in the flight of the ejected escape system.

Obviously for example, if the only way to eject the escape device is to pass it out in a direction, say, parallel to the long axis of the seated torso but the expectation of a one "g" ambient acceleration vector 70° forward of the torso ~~center~~ indicates that the ideal direction is along a path more than 90° forward of this planned escape route, some sort of compromise must be achieved.

The important conclusion to be made here is not so much what the details of such a compromise shall be, but rather that a heretofore unrecognized, or at least undescribed, problem exists which requires consideration and if need be, compromise.

RECOMMENDATIONS

A frustrating aspect of the present study is its limited scope, both in the range and number of parameters under the control of the experimenter and in the level of sophistication in statistical analysis achieved in the analysis of the data. It is recommended, therefore, that three things be done. First, using the results of the present study as indicators, statistical models should be tentatively prepared for describing the nature of the distribution of human centers of gravity (under the conditions simulated) as certain physical parameters vary.

Such models would, while handily summarizing new data, also make possible a search for parameters which significantly affect the location of the human center of gravity.

Second, additional experimental evidence of changing human centers of gravity should be collected, but in three dimensions and under varying levels of three physical parameters: body posture, direction of acceleration, and amplitude of acceleration.

It is impossible at this point to determine from the data at hand the complete relationship of body centers of gravity change to all directions of acceleration, even with such self-imposed limitations of physical conditions as but one body posture and one level of amplitude of acceleration.

This being so, the limits of the domain of the complex set of interactions and resultant effects upon the center of gravity of the human operator is almost beyond being speculated upon.

A third program which should be accomplished to provide realistic estimates of the reliability (safety) of an escape system is the combining of a mathematical probability model of the manufacturing and/or burning variability in rocket thrust vectors with the mathematical probability model of the distribution of individual and mean centers of gravity. These two models, combined further with a model of expected ambient acceleration vectors associated with the aircraft and type of mission, would yield a useful model for predicting the total reliability of an escape system (neglecting of course individual component and subsystem reliabilities).

At a period in the history of aviation when the root of even the word might better refer to space (space-iation...?) it would seem desirable to consider, in the calculations of hardware mass distributions and changes necessary for successful space flight and encapsulated re-entry, the mass distribution of the human component as well - particularly if it changes significantly and quite particularly if eventually there are to be many human components in one vehicle.

Thus, additional research would seem justifiable. It may, as just one example of practical aspects, be possible to determine one or a small set of body postures which yield by their very nature minimum variability in center of gravity change with changing acceleration. This being the case, a valuable new criterion might be added to those which are currently used to stipulate the body posture of operators of aerospace systems.

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