

CHAPTER IV
THE INERTIAL PROPERTIES OF THE BODY AND ITS SEGMENTS

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The purpose of this chapter is to present a user-oriented summary of the current state of knowledge on the mass distribution properties of the adult human body. Design engineers, the most common users of such data, have two sources of information for establishing human biomechanical limitations relevant to their design product. These are directly measured data and output from mathematical models. Empirical data are obviously the more desirable but are often either unavailable or unattainable on living subjects so the output from mathematical models becomes the sole source of design information. These models have, in the past, been based upon the properties of geometric analogues of body segments. While this approach serves a useful purpose in examining population problems where the variation in the population is greater than the error in the model, it does not provide a design engineer with the needed sensitivity to design equipment for a highly selected group of astronauts.

Collected here for the first time are all the known data describing the mass distribution properties of the body presented in such a manner that mathematical models can be highly individualized. This material, which includes data for living whole bodies in static positions and segment data obtained from cadaver studies, will provide both direction for constructing mass distribution models and a range of values by which the model output can be evaluated.

Mass distribution properties will be discussed in terms of the musculoskeletal linkage system, axes systems, mass, volume, center of mass, and inertial properties. In the following sections data and prediction equations or coefficients suitable for modeling these properties are provided.

Predictive formulas presented in this chapter and suitable for both the whole body and its segments will employ, primarily, total body weight and stature as the independent variables. While some computations have been completed and presented here, the user may be interested in computing for a different population. In this case either an individual's measured height and weight could be used or the appropriate population statistics (See Chapter III) could be substituted.

While the prediction equations and resulting estimates will be of use in the preliminary analysis of the design problem for a population, they will not be sensitive to individual variations which may be of significance in designing for a specific astronaut or scientist. For this purpose the reader

will be referred to various tables in Appendix B in which data and computation techniques for estimating the biomechanical properties of the individual appear. Equations provided in this Appendix are aimed at describing segments of the body in such a way that differences between individuals can be observed and will help the designer determine the range and extent to which a particular piece of equipment needs to be personalized. These data also provide biomechanical input for individualized models useful in solving workspace design problems or analyzing dynamic environments.

Data Sources and Limitations

The data and prediction equations presented in this chapter are based, in general, on small samples of living and cadaveric subjects typical of the White European male. In the very few cases where data were available on males and females of other races, the information has been reviewed and incorporated in the appropriate table or prediction equations. However, the fact that most of the data were collected on white European males presents an undeniable problem to the design engineer concerned with a population whose range in size goes from the fifth percentile Oriental woman to the 95th percentile Caucasoid male.

Many different techniques have been utilized for measuring the mass distribution properties of the whole body. Hay (1973) gives an excellent review of these studies and points out the two major difficulties in studies of the living; (1) fluid and tissue shifts in the measurement procedure and (2) the static, or position-dependent, nature of the measured locations. When a whole body is measured, the data are completely valid only when applied to a body in that position. Thus, in order to determine the location of the center of mass for any given body, it is necessary to measure either every possible body position or to measure the location of the center of mass in each body segment and model the whole body from the sum of its segments. The latter approach has been emphasized in the present chapter since it provides information on a wider range of body types and body positions.

The segment model approach has been a recent development and most of the data are derived from European and U.S. studies of cadavers (Harless, 1860; Braune and Fischer, 1889, 1892; Fischer, 1906; Dempster, 1955; Clauser et al. 1969; and Chandler et al. 1975). Two additional studies by Mori and Yamamoto (1959) and Fujikawa (1963) provide some data on the mass distribution of twelve Japanese cadavers. Although the total sample size from all the above-mentioned studies is limited, it probably provides a better estimate for the desired biomechanical properties than do the present geometric models.

Measurements on the body segments of living subjects have usually relied upon indirect methods. Segment weight has been estimated by measuring segment volume (Drillis and Contini, 1966) and by measuring the reaction change on a weight board due to segment displacement (Bernstein et al. 1931). Segment center of mass measurements have used volumetric estimates

(Bernstein et al. 1931; Cleaveland, 1955). Inertial data have been collected almost exclusively on the links using indirect measurement techniques to estimate a single moment of inertia about a joint center of rotation (Fenn, Brody, and Petrilli, 1931; Fenn, 1938; Hill, 1940; Bouisset and Pertuzon, 1968, Allum and Young, 1976). These techniques, in general, assume knowledge of segment density, segment center of mass, and joint centers of rotation depending upon the variable under investigation. A promising indirect technique for measuring the mass distribution properties of the living human body appears to be stereophotogrammetric measures of volume as developed by Herron et al. (1976).

In addition to the lack of complete population data, there are no data on the effect of the secular increase in size on the mass distribution properties of the human body. It has been assumed that these changes will be proportional, thus making a linear solution to any problem possible. For example, if an increase in stature of 0.5% occurs in the next 10 years it is assumed that there would be a corresponding increase in link length. Furthermore, the assumption is made that statistical relationships would remain the same, e.g., the correlation coefficient between acromion-radiale length and stature would remain constant. The design engineer and modeler should be alerted to these kinds of assumptions (which we make, for example, in combining linkage data from Dempster, 1955, and Snyder, Chaffin, and Schultz, 1972) so that he can assess the data within his tolerance limits and decide on the extent to which these data can be relied upon.

Two further limitations of the basic data should be mentioned before proceeding.

First, the relationship between data collected from living subjects and data based on cadaver studies has never been defined. This means that it is not yet known how accurately data garnered from a cadaver can be applied to the living. In addition, the error in estimating data from indirect measurements made on living subjects has also not been defined.

Secondly, all data so far collected were measured at one-g and the changes which a zero-g environment effect on an individual were not considered. One means of dealing with this problem is discussed in following sections on linkage and mass.

The Anatomical Framework

The human body is often compared to a machine. Persuaded by this concept, one is easily led to rely on mechanical concepts to describe the geometry and motion of the body in the biomechanical framework. However, one must recognize that the present mechanical treatment of the human anatomy with mechanical analogies is only an approximation of a highly complex and variable system. As a first step in clarifying the construction of the human body, an anatomical description of joint centers of rotation, axes systems, and body linkages is given in great detail in Appendix A. The user of

this chapter is strongly urged to read this Appendix and obtain some grasp of the anatomical structure that underlies all these biomechanical data. Without a thorough understanding, the user is likely to go astray in applying the data.

In the study of anatomy, three planes--sagittal, frontal, and transverse--have been hypothetically superimposed on the body to describe the relative location of its anatomical features. The usual directional notation system used to describe locations relative to these planes is as follows with the corresponding, right-hand rule axis system nomenclature in parenthesis:

- Anterior--towards the front (+X)
- Posterior--towards the rear (-X)
- Lateral--towards the side: Left (+Y), Right (-Y)
- Medial--towards the middle: Left (-Y), Right (+Y)
- Superior--towards the head (+Z)
- Inferior--towards the feet (-Z)

With the body in the standard anatomical position, the sagittal plane is defined by the X- and Z-axes; the frontal, or coronal, plane is defined by the Y- and Z-axes; and the transverse, or horizontal, plane is defined by the X- and Y-axes (See Figure 1). This superstructure of intersecting planes has not traditionally been anchored to any single location in the body. For biokinematic research and engineering hardware design a whole body axis system should be fixed (rather than "floating") through use of specific anatomical or anthropometric landmarks. The axes proposed in this chapter use three definable landmarks selected so that they form a plane approximately parallel to one of the cardinal anatomical planes of the body. A right-handed, orthogonal axis system is then constructed using the anthropometric plane of orientation, a perpendicular plane and a plane normal to the other two planes. Thus, the axis system will be defined by the intersection of three orthogonal planes of reference and a defined point of origin.

Although a number of axes systems have been proposed (Santschi et al. 1963; Ignazi et al. 1972; and Chandler et al. 1975; Panjabi et al. 1974; Thomas et al. 1975) the whole body axis system which appears at this time to be best suited for biomechanical models is one centered on the pelvis (See Figure 1).

There are several reasons for choosing this system. First, the center of mass of the whole body in every position is approximately at the site of the pelvis. Second, the pelvis can be treated as a rigid body. Third, the human body in its most elemental form is hinged at the pelvis. In other words, a major controlling factor in attitude and motion of the body is the spatial orientation and location of the pelvis.

Therefore, it is recommended that a frontal plane (YZ) be established using symphysis and the right and left anterior superior iliac spines. The transverse (XY) plane is constructed as a perpendicular to the YZ plane while passing through the right and left anterior superior iliac spines. The sagittal (XZ) plane is constructed as a normal to the YZ and XY planes while pass-

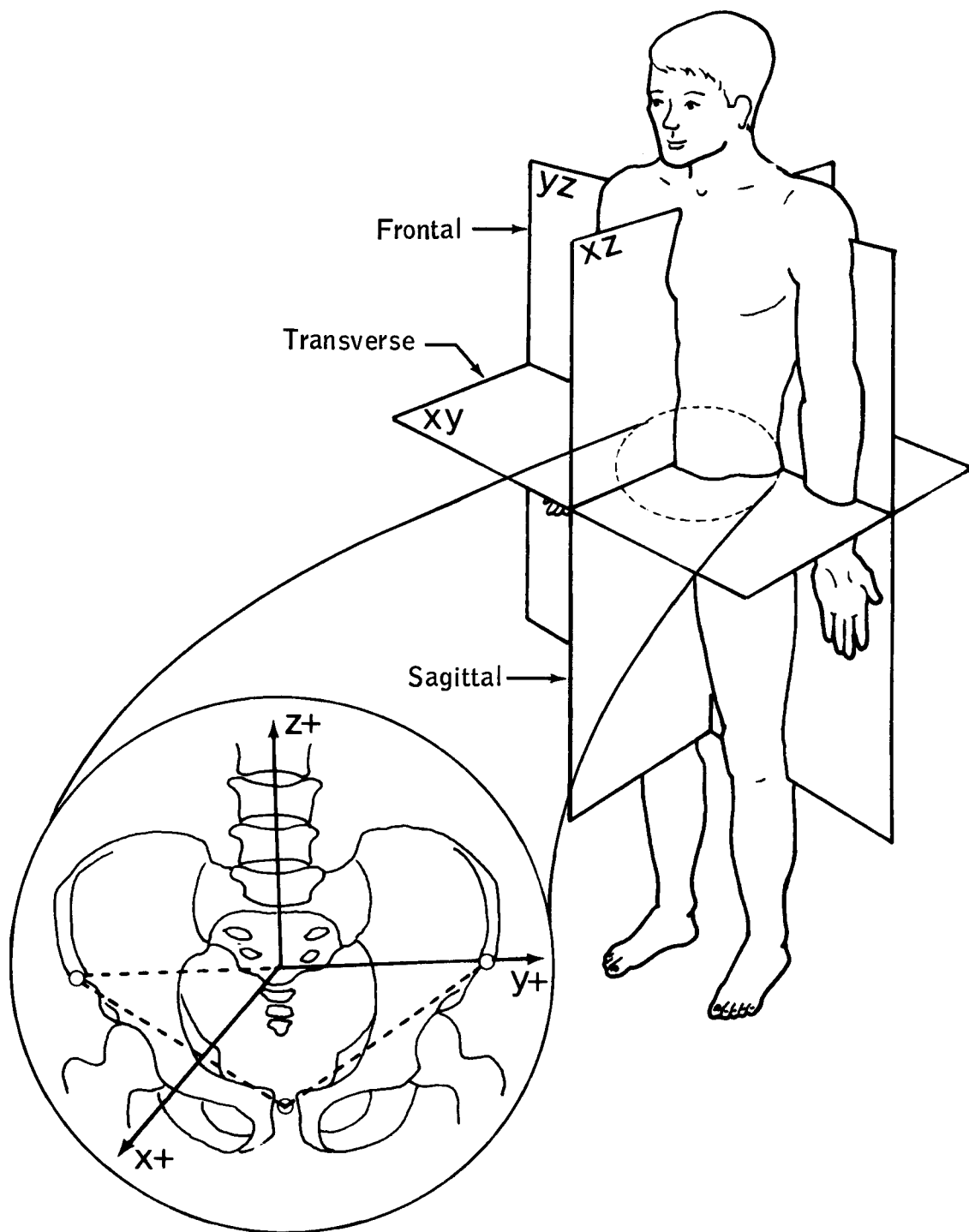


Figure 1. Whole body axis system centered on the pelvis.

ing through symphysis. The coordinate axis system origin will lie on a line passing through the right and left anterior superior iliac spines approximately at the midpoint of bispinous diameter. The +X axis will pass anteriorly along the intersection of the XY and XZ planes; the +Y axis will pass laterally along the intersection of the XY and YZ planes; and the +Z axis will pass superiorly along the intersection of the XZ and YZ planes.

Similar frames of reference have been provided for body segments (See Appendix A). Theoretically, a biomechanical segment of the body is the largest dimensional mass which, when moved, will maintain a constant geometry. Thus, body segments are defined as the mass which lies between two adjacent segmentation surfaces which pass through their respective joint centers of rotation. For example, the forearm is a biomechanical body segment since it has a mass that lies between the wrist and elbow joint centers of rotation. It is, in other words, a body link--a term borrowed from rigid body mechanics which is used frequently to refer to the straight-line distance between two adjacent joint centers of rotation.

In general, the principal body segments are easily identified although the specific segmentation planes and their locations are not as easily determined. The number of principal body segments differ in the literature, particularly with respect to the torso which has been segmented into individual vertebral sections (Liu and Wickstrom, 1973) and left intact as one mass (Chandler et al. 1975). Other segmentation schemes utilized in mass distribution studies have been described in Reynolds et al. (1975). In addition, there are differences in segmentation planes between studies conducted on living subjects and cadavers (See Figure 2).

For the present chapter, the segmentation planes will follow the rationale first presented by Braune and Fischer (1892) and simulated in subsequent studies. This scheme segments the body at the level of joint centers of rotation thereby providing data correlated with the linkage system of the body. Dempster (1955) and Snyder et al. (1972) have provided the basic data we will use here in describing the linkage system and its spatial description.

This chapter is a result of sorting through numerous alternatives to arrive at an anatomical framework most suitable for biomechanical research. The data reflect this approach but without a thorough appreciation of the implications of a mechanical model upon the anatomical reality, costly mistakes and misinterpretations can occur. Therefore the user is once again encouraged to become familiar with Appendix A for a full appreciation of the information contained in this chapter.

The Body Linkage System

A description of the body as a linkage system provides a biomechanical framework that can be used to undertake a rigorous analysis of its kinematics. Without this basic model, the study of the motion of the body and its respective segments would be extremely difficult, if not impossible.

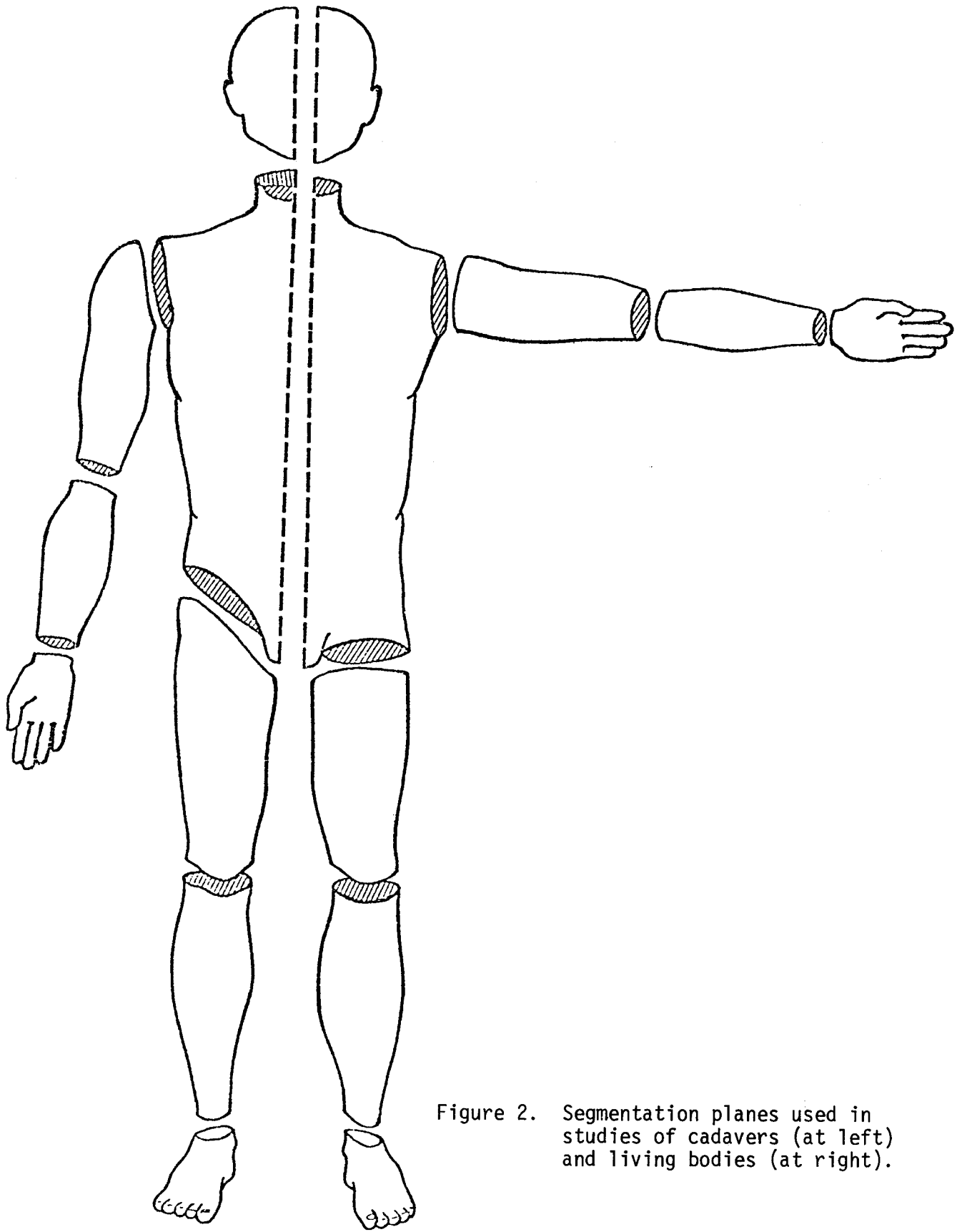


Figure 2. Segmentation planes used in studies of cadavers (at left) and living bodies (at right).

It should be noted, before proceeding, that the concepts of body segments and body links must be handled carefully. The concept of a body segment is useful in describing mass distribution; the concept of a body link is used when describing body motion. When dealing with the limbs, segments and links generally correspond. The torso, however, has such complex motion capabilities that its various segments often contain more than one link.*

For the purposes of this chapter, the body is composed of 20 links: head, neck, thoracic, thoraco-sternum assemblage** (right and left transthoracic and transternum), right and left clavicular, right and left scapular, lumbar, pelvic assemblage** (right and left ilio-pelvic and transpelvic), right and left upper arm, right and left forearm, right and left thigh, right and left shank, right and left foot. These links are illustrated in Figure 3 and defined in Appendix A.

Theoretically, links are pure straight line distances between centers of joint rotation. In fact, due to the complex nature of actual joint motion, the link is an average straight-line distance calculated from points at the mid-range of joint mobility. For a more complete discussion of the body linkage system and the underlying anatomical assumptions, the reader is referred to Dempster's "Space Requirements of the Seated Operator" (1955).

Limb Links

The first step in determining the length of links in the arms and legs is to determine lengths of the relevant long bones, which in turn can be estimated from stature. Then, using coefficients which have been derived as a ratio of link length to bone length, link lengths are determined by multiplying bone lengths by the link/bone coefficients. A step-by-step description of these procedures follows:

The four limb links and their associated bones are: upper arm (humerus), forearm (radius and ulna), thigh (femur), and shank (tibia and

* Insufficient research has been conducted to resolve in a logical and consistent manner the apparent conflict between torso links and segments.

** Both of these linkage assemblages are closed systems composed of three straight-line distances and three joint centers of rotation. They are considered assemblages, at present, since no one straight-line distance in an assemblage can move independently of the other two.

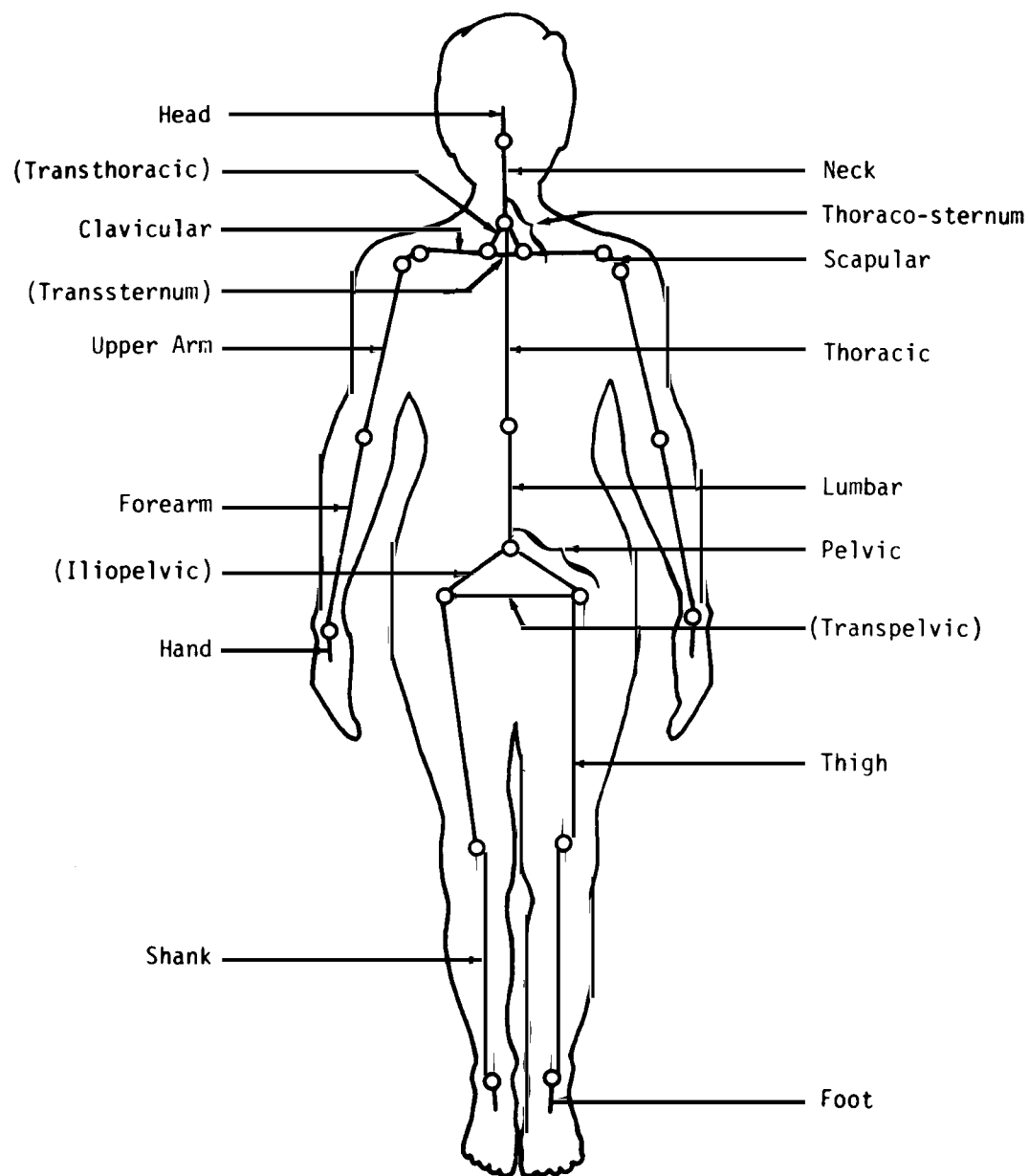


Figure 3. Linkage system.

fibula). In the following discussion and accompanying tables it will be noted that the shank link is presented for tibia length only, whereas the forearm link is described relative to either the radius or ulna. This discrepancy in treatment between the shank and forearm, both of which have two long bones, probably arises as a result of past practice among anthropometrists to measure tibial length rather than fibula length and to measure either of the long bones in the forearm. Design engineers may use either ratio for the forearm or choose to average the relatively small differences between them.

Link lengths in this chapter have been obtained by combining data from two studies: Trotter and Gleser (1958) who measured long bones in the arms and legs using standard osteological techniques, and Dempster, Sherr and Priest (1964) who developed coefficients and regression equations for predicting bone and link lengths.

First the bone length and stature for the sex and race groups in Trotter and Gleser (1958) were normalized in the following manner:

$$\frac{\text{Bone Length} - \text{Mean Bone Length}}{\text{Bone Length Standard Deviation}} \quad (1)$$

and,

$$\frac{\text{Stature} - \text{Mean Stature}}{\text{Stature Standard Deviation}} \quad (2)$$

Next, a linear relationship between the two normalized variables was assumed and the following equation was constructed using the correlation coefficient as the regression coefficient, or slope, with an intercept equal to zero:

$$= \text{Corr. Coef.} \cdot \frac{\text{Bone Length} - \text{Mean Bone Length}}{\text{Bone Length Standard Deviation}} \quad (3)$$

with

$$S_{e_{est}} = \text{Bone Standard Deviation} \sqrt{1 - (\text{Corr. Coef.})^2} \quad (4)*$$

By substituting the appropriate variables from Trotter and Gleser (1958) into equation #3 and solving for the dependent and independent variables, the standard regression equation is generated in the form:

$$y = bx + a** \quad (5)$$

*The derivation of these equations can be found in Croxton (p. 175-176, 1959).

**Where y=bone length, x=stature, b=slope and a=intercept.

with an accompanying standard error of the estimate (equation #4). Table 1 presents the regression equations derived to predict bone lengths from stature for white and black American females and white American, black American, and Oriental males.

To use these equations, an appropriate value for stature is selected and inserted into the equation which is then solved for the appropriate bone length. The same stature value is used for all bone lengths to describe a particular individual or group of individuals. Table 2 presents values derived from the equations in Table 1 for 5th, 50th, and 95th percentile stature data predicted for white males and females in 1985 (See Chapter III, Appendix B).

For these bone length estimates, Dempster, Sherr, and Priest (1964) have provided coefficients to estimate the corresponding link length. Table 3 presents these coefficients which have been derived as a ratio of link length to bone length.

To compute link lengths, the coefficients presented in Table 3 are multiplied by the bone lengths calculated from equations in Table 1. In the present case, the data in Table 2 have been multiplied by the appropriate coefficients in Table 3 to generate the link lengths presented in Table 4. It is interesting to note that the coefficients in Table 3 were computed from data on male whites only and yet the results in Table 4 appear, on the basis of the forearm link, to estimate the link lengths of females with better correspondence between estimates than for males.

Dempster, Sherr and Priest (1964) also derived regression equations to estimate link lengths directly from anthropometric measures of bone length (See Appendix B, Table 1). When bone length data are available for individual astronauts, for example, these equations can be used to estimate individual link lengths more precisely.

Link lengths for the hands and feet are calculated from the wrist and ankle joint centers to the respective centers of mass. These data are presented in the next section in which the segment centers of mass are discussed. However, Dempster (1955) provides two coefficients to estimate hand and foot links. The hand link is estimated as 20.6% of humerus length (See Table 1); the foot link is estimated as 30.6% of foot length (See Chapter III).

Head and Torso

The torso with its unique characteristics of motion and the complex spatial relationships of its parts is the most difficult part of the body to describe within the linkage framework. While a number of approaches are possible, the input parameters used to describe the kinematic properties of the torso in this chapter will be relative to three links for the spinal column (neck, thorax, and lumbar), a link assemblage for the pelvic girdle

TABLE 1
REGRESSION EQUATIONS FOR ESTIMATING LIMB LENGTHS*

<u>Female</u>				<u>Se_{est}</u>
a) White				
Humerus Length	=	0.1855	stature +	0.771 (+1.03)
Radius Length	=	0.130	stature +	1.273 (+0.76)
Ulna Length	=	0.139	stature +	1.708 (+0.89)
Femur Length	=	0.289	stature -	3.516 (+1.30)
Tibia Length	=	0.242	stature -	4.870 (+1.15)
Fibula Length	=	0.243	stature -	4.695 (+1.13)
b) Black				
Humerus Length	=	0.181	stature +	1.699 (+1.05)
Radius Length	=	0.143	stature +	0.580 (+1.14)
Ulna Length	=	0.130	stature +	4.535 (+0.99)
Femur Length	=	0.310	stature -	6.214 (+1.27)
Tibia Length	=	0.265	stature -	7.221 (+1.25)
Fibula Length	=	0.261	stature -	6.471 (+1.22)
<u>Male</u>				
a) White				
Humerus Length	=	0.185	stature +	1.338 (+1.17)
Radius Length	=	0.137	stature +	1.467 (+0.89)
Ulna Length	=	0.140	stature +	2.688 (+0.93)
Femur Length	=	0.281	stature -	1.902 (+1.44)
Tibia Length	=	0.268	stature -	8.369 (+1.33)
Fibula Length	=	0.257	stature -	6.490 (+1.22)
b) Black				
Humerus Length	=	0.202	stature -	0.969 (+1.13)
Radius Length	=	0.157	stature -	0.599 (+1.02)
Ulna Length	=	0.158	stature -	1.013 (+1.06)
Femur Length	=	0.314	stature -	9.740 (+1.49)
Tibia Length	=	0.288	stature -	9.740 (+1.40)
Fibula Length	=	0.266	stature -	6.129 (+1.32)
c) Oriental				
Humerus Length	=	0.213	stature -	4.028 (+1.22)
Radius Length	=	0.160	stature -	2.364 (+0.98)
Ulna Length	=	0.158	stature -	0.244 (+1.03)
Femur Length	=	0.303	stature -	6.621 (+1.48)
Tibia Length	=	0.292	stature -	12.951 (+1.14)
Fibula Length	=	0.303	stature -	14.659 (+1.14)

*All values are given in centimeters. To convert to inches, multiply by .3937.

TABLE 2
BONE LENGTH VALUES ESTIMATED FOR 1985 POPULATION*

<u>Limb</u>	<u>Male White</u>			<u>Female White</u>		
	5th	50th	95th	5th	50th	95th
Humerus	32.03 (12.61)	34.08 (13.42)	36.16 (14.24)	29.23 (11.51)	31.12 (12.25)	32.96 (12.98)
Radius	24.20 (9.53)	25.72 (10.13)	27.25 (10.73)	21.22 (8.35)	22.54 (8.87)	23.83 (9.38)
Ulna	25.91 (10.20)	27.47 (10.81)	29.04 (11.43)	23.03 (9.07)	24.45 (9.63)	25.82 (10.17)
Femur	44.72 (17.61)	47.84 (18.83)	50.98 (20.07)	40.82 (16.07)	43.76 (17.23)	46.63 (18.36)
Tibia	36.09 (14.21)	39.07 (15.38)	42.07 (16.56)	32.25 (12.70)	34.72 (13.67)	37.12 (14.61)
Fibula	36.15 (14.23)	39.00 (15.35)	41.88 (16.49)	32.58 (12.83)	35.06 (13.80)	37.47 (14.75)

*Data given in centimeters with inches in parentheses.

TABLE 3
RATIOS OF LINK LENGTH TO BONE LENGTH
(After Dempster, et al. 1964)

Ratio of Lengths	N	Mean	Standard Deviation
Upper Arm Link/ Humerus Length	32	89.44%	1.59%
Forearm Link/Ulna Length	32	98.70	2.66
Forearm Link/Radius Length	26	107.09	3.53
Thigh Link/Femur Length	32	90.34	0.88
Shank Link/Tibia Length	33	107.76	1.81

TABLE 4
LINK LENGTH VALUES ESTIMATED FOR 1985 POPULATION*

<u>Limb</u>	<u>Male White</u>			<u>Female White</u>		
	<u>5th</u> <u>%tile</u>	<u>50th</u> <u>%tile</u>	<u>95th</u> <u>%tile</u>	<u>5th</u> <u>%tile</u>	<u>50th</u> <u>%tile</u>	<u>95th</u> <u>%tile</u>
Upper Arm Link	28.65 (11.28)	30.48 (12.00)	32.34 (12.73)	26.14 (10.29)	27.83 (10.96)	29.48 (11.61)
Forearm Link (Ulna)	25.57 (10.07)	27.11 (10.67)	28.66 (11.28)	22.73 (8.95)	24.13 (9.50)	25.48 (10.03)
Forearm Link (Radius)	25.92 (10.20)	27.54 (10.84)	29.18 (11.49)	22.72 (8.94)	24.13 (9.50)	25.52 (10.05)
Thigh Link	40.40 (15.91)	43.22 (17.02)	46.06 (18.13)	36.88 (14.52)	39.53 (15.56)	42.13 (16.59)
Shank Link	38.89 (15.31)	42.10 (16.57)	45.33 (17.85)	34.75 (13.68)	37.41 (14.73)	40.00 (15.75)

*Data given in centimeters with inches in parentheses.

(right and left ilio-pelvic and transpelvic), and five links for the shoulder girdle (thoraco-sternum assemblage, right and left clavicular, and right and left scapular). These links are defined in Appendix A and illustrated in Figure 3.

A fairly complete discussion of some of these links can be found in Dempster (1955). He provides coefficients based on cadaver data for estimating the clavicular and transpelvic links. The clavicular link is estimated as 35.2% of biacromial breadth (See Chapter III); the transpelvic link is estimated as 37.2% of femur length (See Table 1). He did not provide coefficients for estimating any of the remaining links in the torso. Thus, with the publication of Dempster's work on the linkage system of the human body, the links in the appendages were defined quantitatively, the links in the shoulder and pelvic girdles were identified and the links in the spinal column were as yet unstudied.

In 1961, S. P. Geoffrey attempted to establish the spatial relationship between the hip joint center and the shoulder joint center. This is the only extant quantitative description of the distance between the shoulder and hip joint centers of rotation. Geoffrey studied twelve men to locate these joint centers radiographically in the sagittal plane for the purpose of constructing a two-dimensional design manikin. The average distance between the shoulder joint center and the hip joint center is 47.4 cm (18.67 in.)

which is representative of the average joint center-to-joint center dimension in the erect seated position for a 50th percentile 1985 male.

The next attempt to examine the torso linkage system was made in 1972 by Snyder, Chaffin, and Schutz. Their report contains a prediction model of torso mobility relative to two reach envelopes for the right elbow. Their data define the configuration of a collection of discrete skeletal landmarks for a specific elbow reach position; the data do not describe interrelationships between these landmarks which would define the torso linkage system. We will not attempt here to synthesize their model or to draw conclusions from it. Rather, we will encourage the reader to refer to the original publication.

A computer model developed for this chapter has produced the illustrations in Figures 4, 5, 6, and 7. These stick figure drawings depict a 50th percentile 1985 male in a seated reach configuration typically encountered in work environments. This model is based upon equations developed in the Snyder et al. study, as well as equations for the limbs presented in Table 1. As can be observed in the illustrations, there are spatial data on a large number of skeletal landmarks. These landmarks represent typical candidates in the spinal column for joint centers of rotation from which a linkage system of the spinal column could be developed. The Snyder report contains data on almost all the vertebra in the spinal column, but additional analysis is required to determine the minimum number and location of the links necessary to describe motion in the torso.

At this point, some observations with respect to a general statement concerning our knowledge of the link system is necessary. Dempster has provided us with sufficient information on the linkage system of the appendages to establish useable population estimates. Geoffrey established a dimension for the relationship between the shoulder and hip joint centers but his data are insufficient for population estimates. The most recent attempt by Snyder et al. considers the torso linkage system within the general context of a workspace reach problem. Therefore, there are data available which provide a generalized understanding of the body linkage system, but quantitative population estimates are, at present, unavailable.

In order to complete the current linkage model of the body, substantial information is needed on the pelvic assemblage. Furthermore, subsequent data must be collected relative to standard body dimensions taken in an initial body position used in traditional anthropometry. In summary, a linkage system of the body has been proposed and modeled but not completely validated for any body positions.

The Torso in Zero-Gravity

The torso linkage system discussed above represents the body configuration under one-g conditions (e.g. terrestrial environment) and, for space applications, must be modified to conform with the current understanding of the changes that occur under zero-gravity conditions.

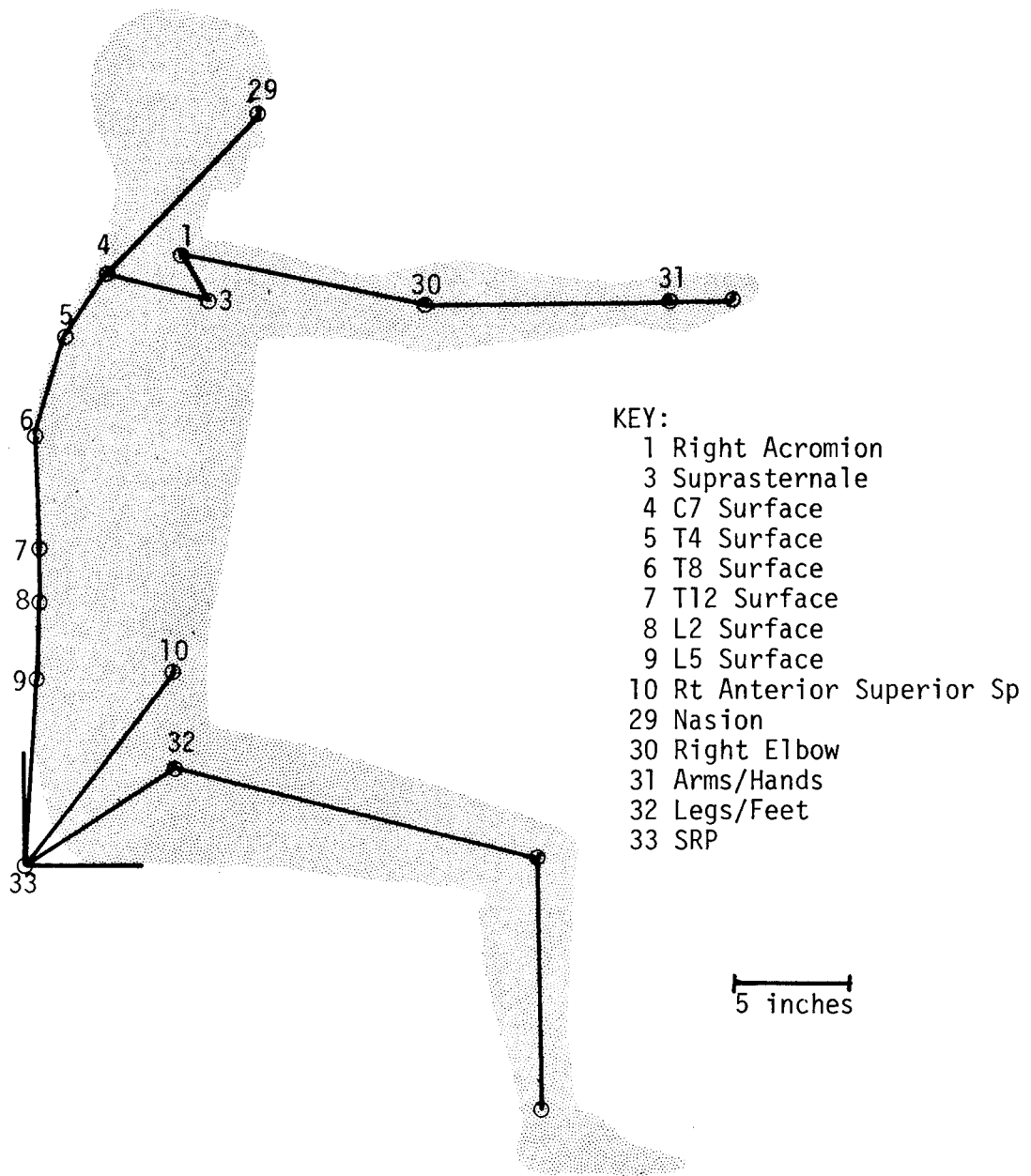


Figure 4. A computer model of body linkage: 50th percentile 1985 man with extended elbow.

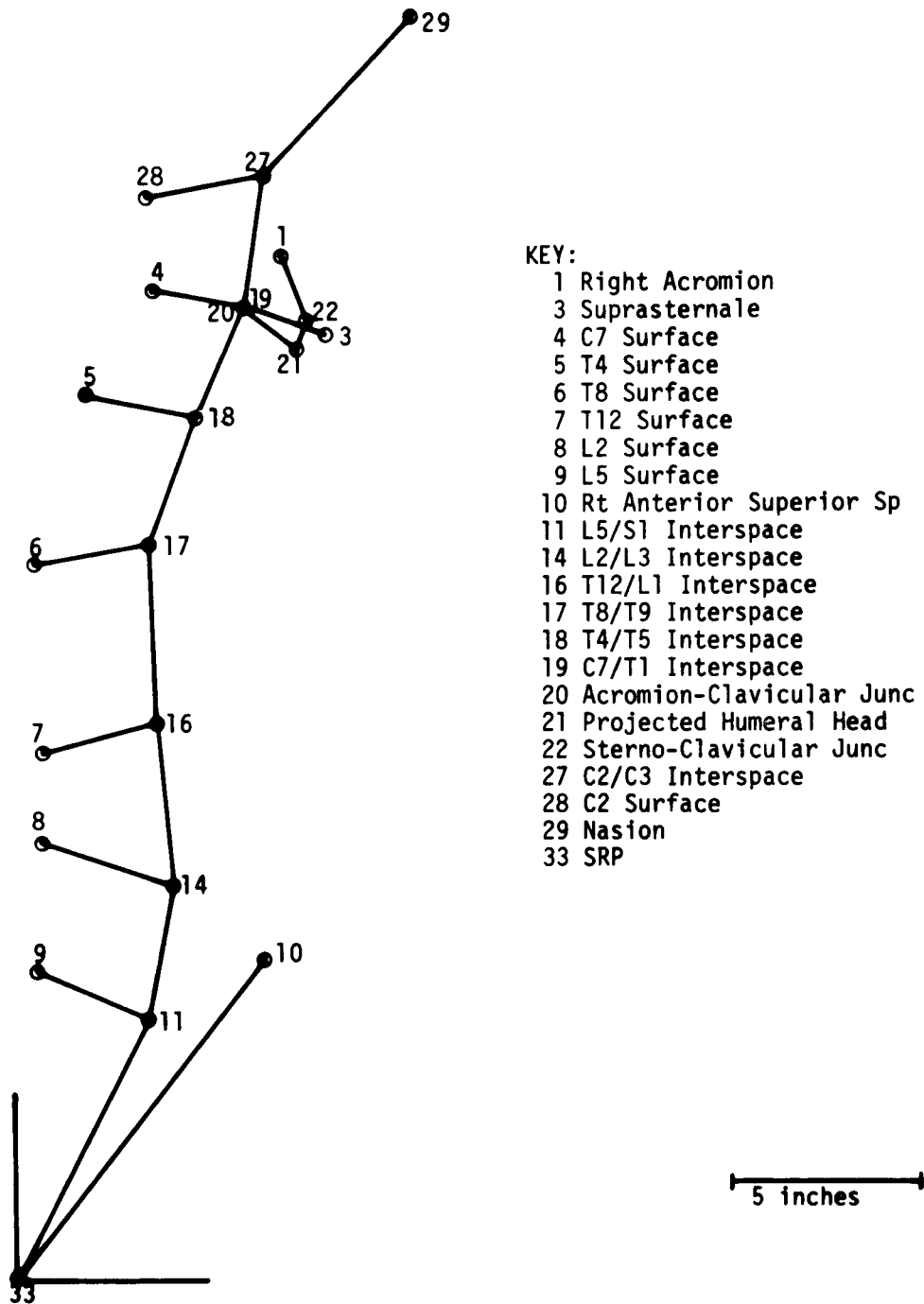


Figure 5. Internal anatomical landmarks of the torso for body position depicted in Figure 4.

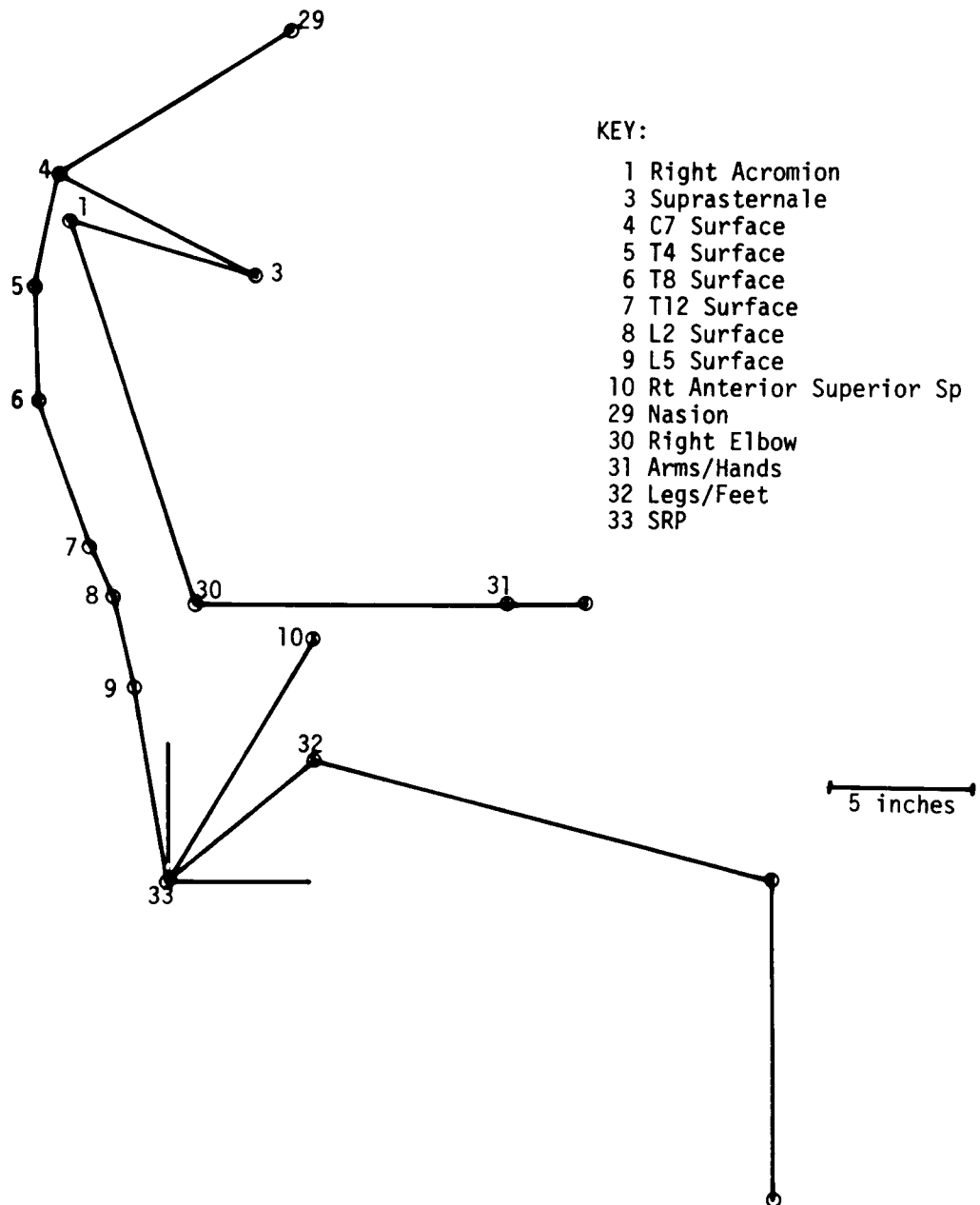


Figure 6. Computer model of body linkage: 50th percentile 1985 man in resting one-g seated position.

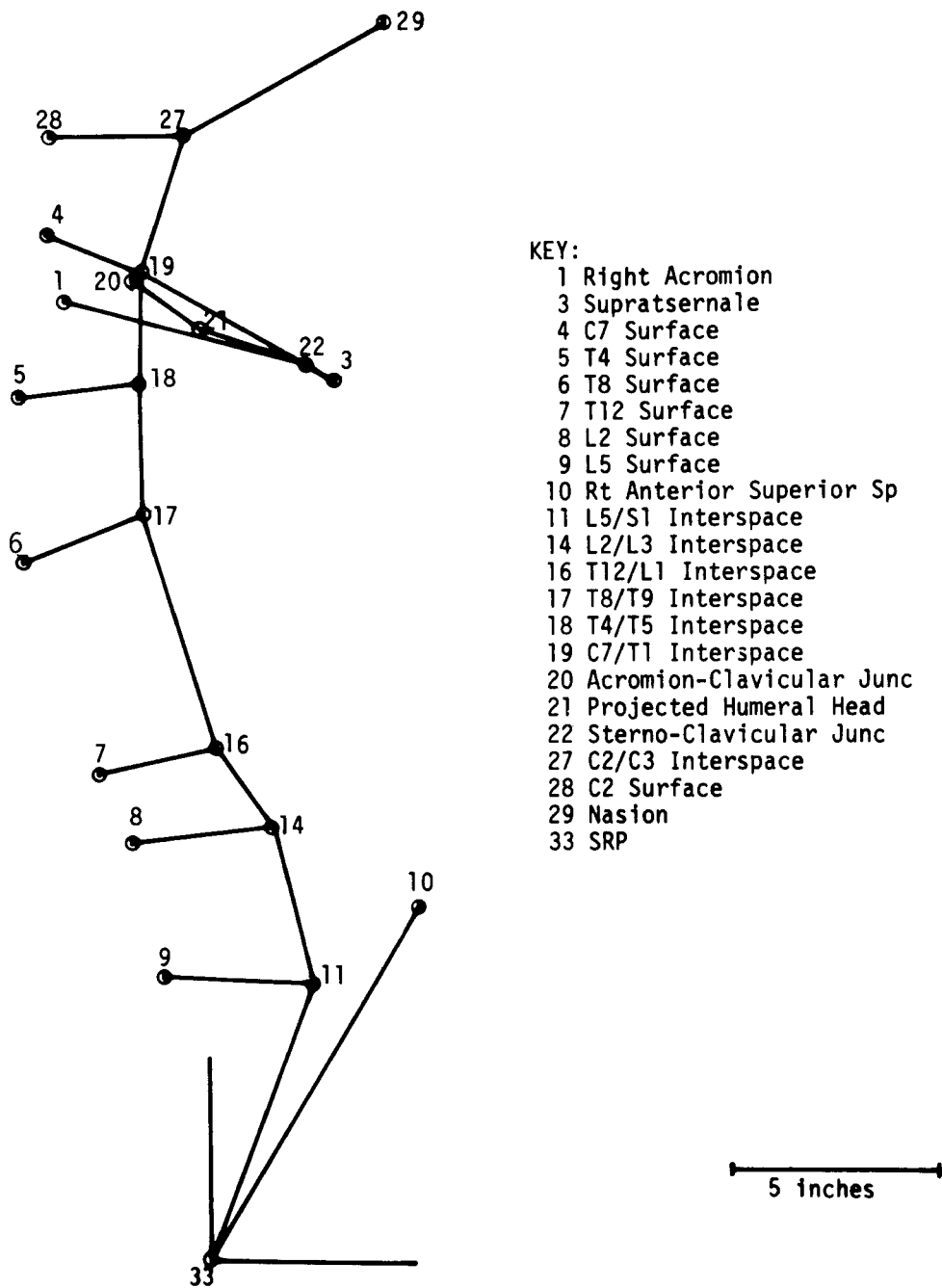


Figure 7. Internal anatomical landmarks of the torso for body position depicted in Figure 6.

It has been reported (Thornton et al., 1974) by astronauts that their stature increases by as much as two inches in space. This increase probably occurs primarily in the torso and only slightly in the lower limbs (knee and ankle joints).

The upright stance of the human body on earth is achieved by means of an S-shaped adaptation in the spinal column which begins as a single continuous curve at birth. In the zero-g environment, gravity no longer acts to compress the spinal column; and the typical lordosis and kyphosis curves in the spine are no longer a functional requirement for upright posture. Figure 8 illustrates the typical relaxed "weightless" posture assumed in the zero-g environment (Jackson, Bond and Gunderson, 1975).

To reflect the elimination of gravitational pull, torso link data must be elongated and straightened. Table 5, based on an analysis of vector distances and angles for all one-g positions reported on in Snyder et al. (1972), portrays the effects of modifying the link data. By allowing for a 5% intervertebral expansion factor and straightening the curved spinal column, approximately 3.7 cm (1.5 inches) of "growth" can be explained. This growth will obviously be subject to individual variations in both expansion among the vertebrae and straightening of the thoraco-lumbar spinal column.

TABLE 5
VALUES COMPUTED FROM SNYDER ET AL. (1972) DATA DEMONSTRATING
POSSIBLE SOURCE OF ZERO-GRAVITY TORSO "GROWTH"

<u>Intervertebral Links</u>	<u>Link Length (1-g)</u>	<u>5% Expansion Factor (0-g)</u>
(Expansion)		
L5/S1 - L4/L5	3.66 (1.44)	.18 (0.07)
L4/L5 - L3/L4	3.63 (1.43)	.18 (0.07)
L3/L4 - L2/L3	3.86 (1.52)	.20 (0.08)
L2/L3 - L1/L2	3.63 (1.43)	.18 (0.07)
L1/L2 - T12/L1	3.66 (1.44)	.18 (0.07)
T12/L1 - T8/T9	11.28 (4.44)	.56 (0.22)
T8/T9 - T4/T5	9.47 (3.73)	.48 (0.19)
T4/T5 - C7/T1	8.91 (3.51)	<u>.46 (0.18)</u>
	Subtotal	2.42 (0.95)
(Straightening)		
L5/S1 - C7/T1	46.41 (18.27)	<u>1.30 (0.51)</u>
	Total "Growth"	3.72 (1.46)

*Data given in centimeters with inches in parentheses.

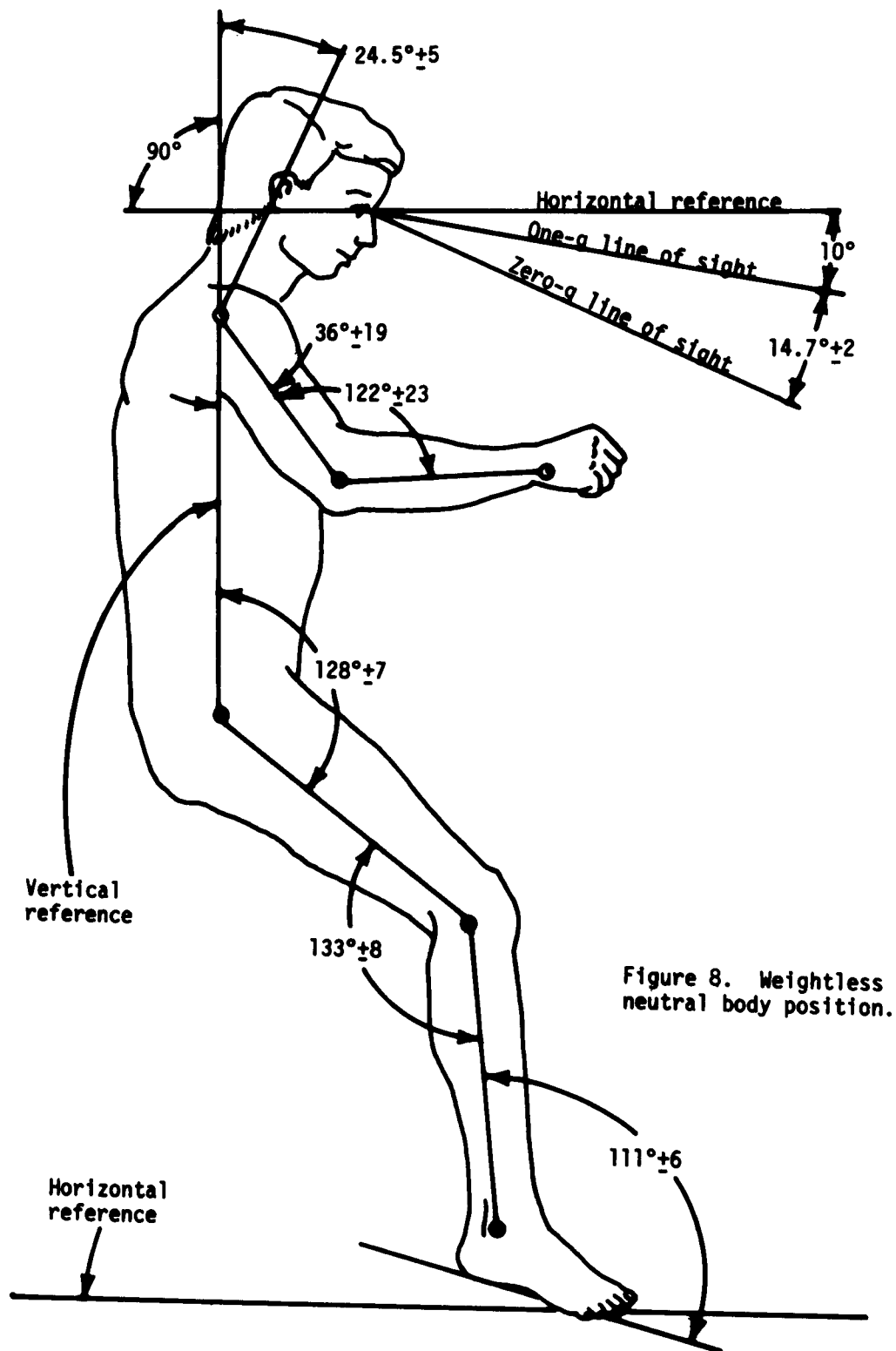


Figure 8. Weightless neutral body position.

Center of Mass

This section will serve as a general guide for locating the whole body center of mass.* The center of mass of the whole body is best predicted from individualized models in which the center of mass is computed from the sum of segments. Measurements of living subjects under one-g conditions have established that the center of mass of the whole body is always in close proximity to the pelvis and appears to remain, regardless of body configuration, at the approximate level of the anterior superior iliac spines. This relationship evidently changes under zero-gravity conditions. Data on the location of the center of mass in static whole bodies and predictive equations for body segments locations will be given in this section.

Most of the whole body center of mass locations have been measured with the body in either a standing or sitting position. Since both living subjects and cadavers have been measured in these studies, comparisons between the two sets of data can be made.

In all of the investigations cited, measurements have been taken with the body in a static position under one-g environmental conditions. As has already been noted, one effect of zero-gravity on the torso is to extend the vertebral column. Another effect is a shift in body fluids, reducing them in the limbs and increasing them in the torso. These conditions, which have the effect of moving the center of mass toward the head, generally describe embalmed cadavers, particularly those stored in the supine position. With the force of gravity acting on the supine body, the vertebral column tends to straighten, thereby extending the torso length. This phenomenon has been noted for the living when, upon rising in the morning, the body is approximately .5 to .75 inches taller than it is at night (Backman, 1924; Damon, 1964). In addition, body fluids in embalmed cadavers tend to pool in the head and torso, since they are generally at the lowest level of the body in the supine position and have a volume of unfilled space greater than other parts of the body. Thus, while the causes of an extension of the vertebral column and a shift in body fluids are not the same in cadavers and living persons in a zero-g environment, the effects are similar.

Much of the data in the following tables have been measured on embalmed cadavers. If the design engineer accepts the assumption that the mass distribution of the zero-gravity astronaut is more analogous to embalmed cadavers than living subjects on earth, then relevant cadaver coefficients and equations should be utilized. There do exist some alternative data from studies in which the location of the center of mass of body segments for living subjects were measured indirectly using volumetric or reaction change techniques. Engineers using these data should be aware of an underlying assumption in this case too, namely, that these results assume constant density throughout the body part measured, thus equating center of mass with center of volume.

*The center of mass measured under zero-gravity conditions and the center of gravity measured under one-g conditions are considered for practical purposes to be the same. The major difference occurs as a result of the force of gravity distorting living tissues and redistributing fluids in the body.

Whole Body

In general, the center of mass in living adult males and females in the standing position is 55% of stature as measured from the floor (Crosky et al. 1922; Cotton, 1931; Hellebrandt et al. 1937; Ignazi et al. 1972; Page, 1974). The center of mass in adult male cadavers is slightly higher at 59% of stature (Clauser et al. 1969; Chandler et al. 1975). Ignazi et al. (1972), confirming that the center of mass is at 55% of stature, further pinpointed the measurement at 97.2% of anterior superior iliac spine height (measuring from the floor), at 50% of bicristal breadth in the y-axis, and 31.7% of a line perpendicular to two parallel lines tangent to the heel and toes (measured from the heel) on the x-axis.

In 1962 Swearingen measured the location of the center of mass of the whole body in 67 positions. His sample consisted of five adult men with an average weight of 163.85 lbs (113.25-225.1 lbs) and an average stature of 68.8 inches (64.75-72.0 inches). Swearingen attempted to define the maximum displacement of the center of mass of the whole body relative to the pelvis.

Swearingen first located the center of gravity for each of his subjects in an initial erect standing body position. All body appendages, including the upper torso were then moved around the pelvis which remained in the same position relative to the measurement device. For example, to determine maximum displacement in an anterior direction, the center of gravity was first located for an erect standing position relative to the position of the pelvis in the measurement device. Keeping the pelvis fixed, the body parts were moved anteriorly to determine the maximum displacement possible. Table 6 defines the spatial envelope within which the location of centers of gravity for most of the common body positions will fall.

On the following pages we present the results of three studies aimed at locating the center of mass in living subjects. The results in all three studies have been reported using different axes systems. However, when the data are examined using comparable axes systems, the differences disappear, or become negligible. (To avoid confusion, the data are reported and illustrated here in their original axis systems.) In all cases, individualized data are presented in the report and if a user needs design information for a specific individual, he is encouraged to utilize the original report and match his subject on the basis of height and weight rather than using the sample summaries reported herein.

In the first study, Santschi, DuBois, and Omoto (1963) measured the location of the center of mass in three axes for eight positions depicted in Figure 9. A summary of their data appears in Table 7 which is presented relative to a right-handed orthogonal axis system. The x-axis shown in the illustration accompanying Table 7 is measured posteriorly to the back plane (YZ). The y-axis is measured as one-half of bispinous diameter in the mid-sagittal plane (XZ). The z-axis is measured superiorly to vertex as a perpendicular to a transverse plane (XY). The average location of the center of mass for this sample of 66 male subjects represents that found in an

TABLE 6
SUMMARY OF MAXIMUM DISPLACEMENT OF CENTER OF GRAVITY FOR
VARIOUS BODY POSITIONS DESCRIBED BY SWEARINGEN (1962)*

<u>Distance</u>	<u>CG Measured From</u>	<u>Direction</u>	<u>Initial Position</u>	<u>Max. Displacement</u>
29.2 (11.5)	Ischium	Towards the head	Erect standing	Seated, arms extended overhead and legs extended and raised maximally towards the head.
25.4 (10.0)	Ischium	Towards the feet	Erect standing	Standing, torso flexed at waist with hands touching floor.
20.3 (8.0)	Back plane	Anteriorly	Erect standing	Sitting with arms and legs parallel, fully extended, and in maximum reach position in the horizontal plane.
11.4 (4.5)	Abdomen plane	Posteriorly	Erect standing	Resting on abdomen with torso flexed posteriorly, arms and legs in maximum posterior reach position.
11.4 (4.5)	Mid-sagittal plane	Laterally	Erect standing	Torso flexed laterally and all body parts moved laterally as far as possible in para-sagittal planes.

*Data given in centimeters with inches in parentheses.

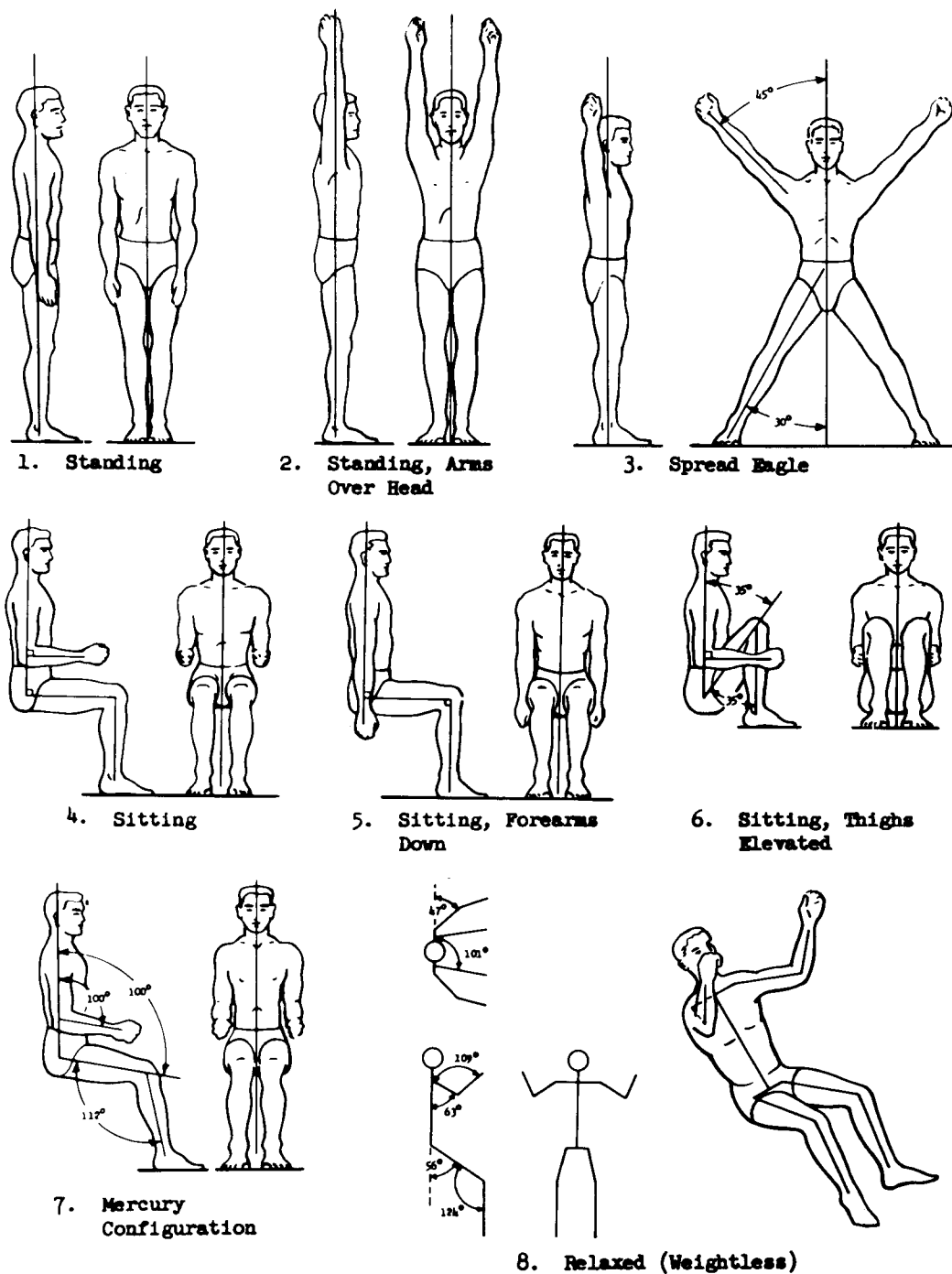
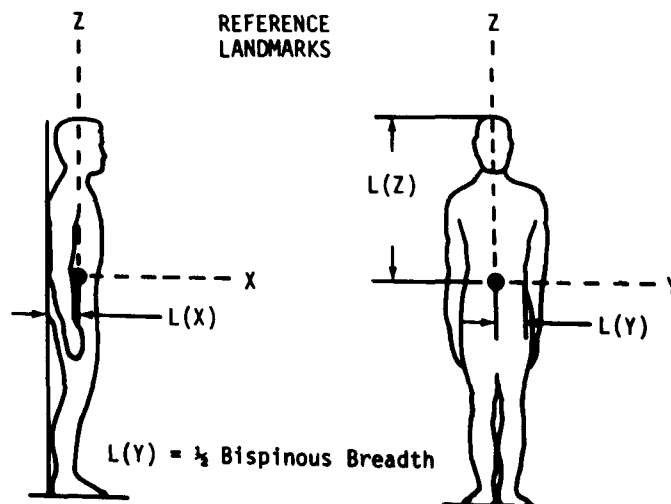


Figure 9. Centers of mass in eight body positions (from Santschi et al. 1963).

TABLE 7
LOCATION OF CENTER OF GRAVITY BASED ON SANTSCI ET AL. (1963)*

			<u>Mean</u>	<u>S.D.</u>
1. Standing	x		8.89 (3.5)	0.51 (0.20)
	y		12.19 (4.8)	0.99 (0.39)
	z		78.74 (31.0)	3.68 (1.45)
2. Standing, arms over head	x		8.89 (3.5)	0.56 (0.22)
	y		12.19 (4.8)	0.99 (0.39)
	z		72.64 (28.6)	3.38 (1.33)
3. Spread eagle	x		8.38 (3.3)	0.48 (0.19)
	y		12.19 (4.8)	0.99 (0.39)
	z		72.39 (28.5)	4.83 (1.90)
4. Sitting	x		20.07 (7.9)	0.91 (0.36)
	y		12.19 (4.8)	0.99 (0.39)
	z		67.31 (26.5)	2.90 (1.14)
5. Sitting, fore- arms down	x		19.56 (7.7)	0.86 (0.34)
	y		12.19 (4.8)	0.99 (0.39)
	z		68.07 (26.8)	2.95 (1.16)
6. Sitting, thighs ele- vated	x		18.29 (7.2)	0.94 (0.37)
	y		12.19 (4.8)	0.99 (0.39)
	z		58.67 (23.1)	1.98 (0.78)
7. Mercury con- figuration	x		20.07 (7.9)	0.86 (0.34)
	y		12.19 (4.8)	0.99 (0.39)
	z		68.83 (27.1)	2.90 (1.14)
8. Relaxed (weightless)	x		18.54 (7.3)	0.84 (0.33)
	y		12.19 (4.8)	0.99 (0.39)
	z		69.85 (27.5)	3.66 (1.44)

*Data given in centimeters with inches in parentheses.



individual slightly smaller than the 50th percentile of the 1985 white European male population.

DuBois et al. (1964) extended the 1963 study to measure the centers of gravity in the sitting and relaxed positions for the nude, unpressurized, and pressurized male wearing the A/P22s-2 full pressure garment. The results are presented in Table 8. It can be noted that the nude data for the x- and y- axes are very similar to the Santschi data; the location of the center of gravity along the z-axis, however, was measured superiorly to the seat pan rather than inferiorly from vertex.

Ignazi et al. (1972) report the only recent European data on the whole body.* Their data are summarized in Table 9. Here, too, the axis system differs somewhat from Santschi's in the z direction since measurements were taken from the floor rather than from center of gravity to vertex. A quick calculation reveals that the z-axis measured from center of gravity to vertex in the Ignazi study averages 31.10 inches compared to 31.0 inches in the Santschi study.

The most rigorous study of the location of the whole body center of gravity can be found in Chandler et al. (1975) which reports the results of an investigation into the inertial properties of six adult male cadavers. Their data locate the center of gravity in three dimensions for three embalmed, cadavers frozen in the standing position and for three embalmed, cadavers frozen in the seated position. These measurements were made on rigid bodies, fixed within a three-dimensional inertial frame of reference, thereby avoiding some of the methodological problems of repositioning living subjects. Furthermore, this study reports measurements of the center of gravity in the y-axis rather than assuming symmetry.

Using the same axis system as utilized by Santschi, a comparison between cadaver and living subject data was made in Reynolds et al. (1975). This comparison reveals that for subjects matched on the basis of stature and weight, differences in the locations of the whole body center of gravity can be ignored for practical purposes. Except in connection with the x-axis in the standing position, differences can be explained by reference to the previously discussed changes in the body of the cadaver stored in a supine position. In general, the differences in mass distribution between a cadaver and a living human reflect shifts in tissue and fluids and a change in spinal configuration.

The magnitude and direction of these differences can be observed in Table 10 which reports the percentage differences between the cadavers in the Chandler et al. (1975) study and living subjects, matched for height

*Despite the differences in average body weight between the Ignazi and Santschi samples, a careful comparison of matched subjects reveals no significant differences in their mass distribution properties. Thus, the differences in the sample means probably reflect sampling differences of statistical origin.

TABLE 8
LOCATION OF CENTER OF GRAVITY BASED ON DUBOIS ET AL. (1964)*

		<u>Mean</u>	<u>S.D.</u>
<u>Sitting</u>	Nude	x	20.04 (7.89)
		y	12.17 (4.79)
		z	23.27 (9.16)
	Unpressurized	x	21.16 (8.33)
		y	12.17 (4.79)
		z	24.79 (9.76)
<u>Relaxed</u> <u>(Weightless)</u>	Pressurized	x	21.89 (8.62)
		y	12.17 (4.79)
		z	24.64 (9.70)
	Nude	x	18.64 (7.34)
		y	12.17 (4.79)
		z	18.77 (7.39)
	Unpressurized	x	19.84 (7.81)
		y	12.17 (4.79)
		z	19.96 (7.86)
	Pressurized	x	20.52 (8.08)
		y	12.17 (4.79)
		z	19.84 (7.81)

*Data given in centimeters with inches in parentheses.

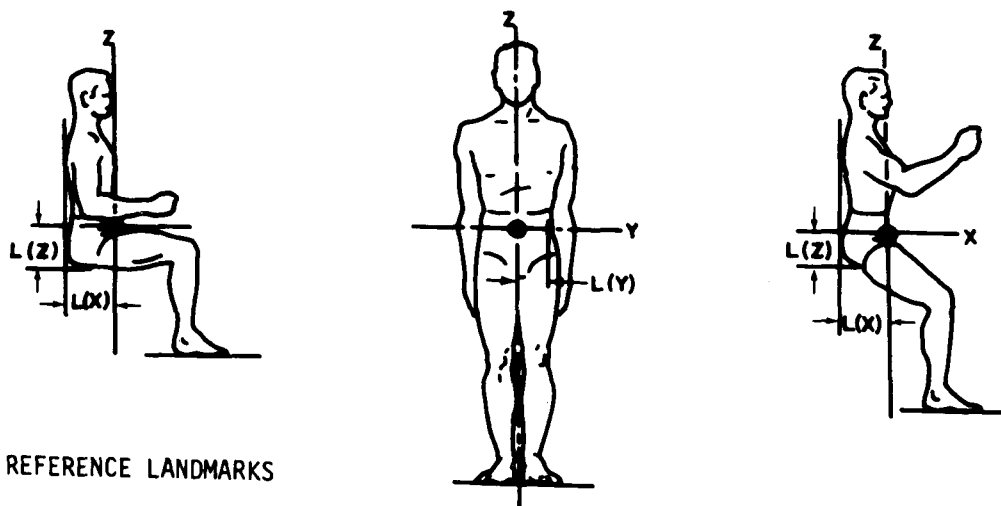


TABLE 9
LOCATION OF CENTER OF GRAVITY BASED ON IGNAZI ET AL. (1972)*

	<u>Mean</u>	<u>S.D.</u>	<u>C.V.</u>	<u>Min.</u>	<u>Max.</u>	<u>Range</u>
x-axis	15.09 (5.94)	1.31 (0.52)	8.71 (3.43)	13.40 (5.28)	17.70 (6.97)	4.30 (1.69)
y-axis	8.83 (3.48)	0.62 (0.24)	6.99 (2.75)	7.60 (2.99)	9.70 (3.82)	2.10 (0.83)
z-axis	96.49 (37.99)	4.25 (1.67)	4.40 (1.73)	86.90 (34.21)	101.10 (39.80)	14.30 (5.63)

*Data given in centimeters with inches in parentheses.

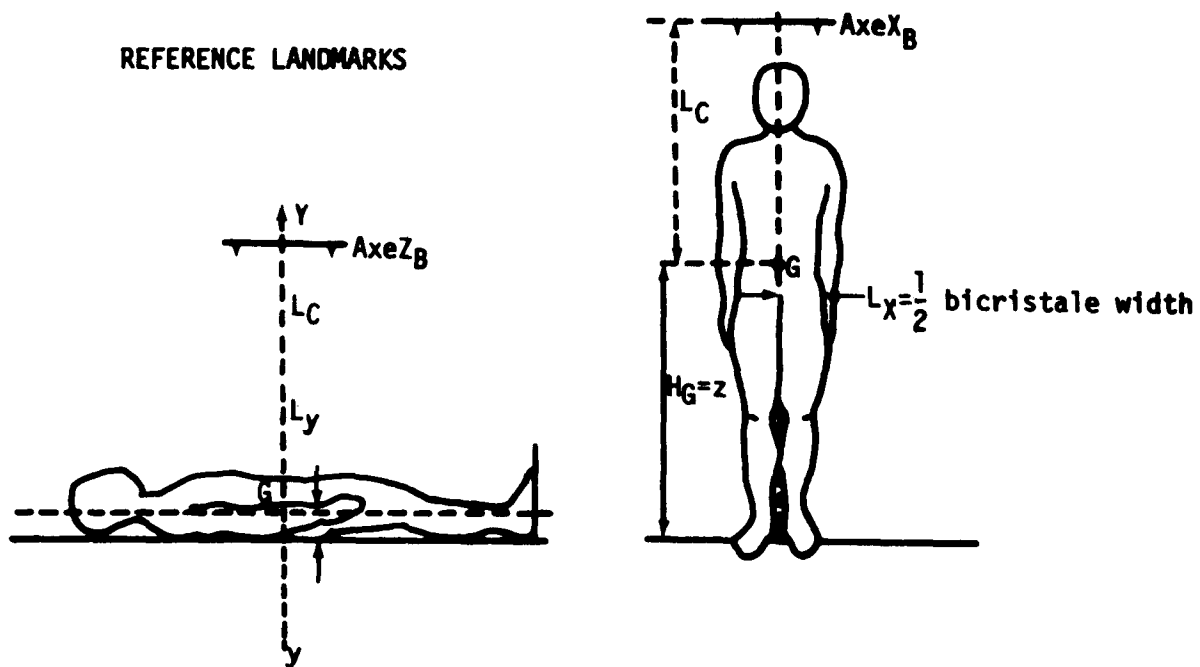


TABLE 10
COMPARISON OF CHANDLER ET AL. (1975) AND SANTSCI ET AL. (1963)
LOCATION OF CENTER OF GRAVITY FOR THE WHOLE BODY IN SUBJECTS
MATCHED ON BASIS OF HEIGHT AND WEIGHT

	<u>Standing</u>			<u>Sitting</u>		
Subject (Chandler & Santschi)	(1 & 19)	(2 & 1)	(3 & 17)	(4 & 26)	(5 & 16)	(6 & 39)
Stature	-2.3%	-1.0%	-0.7%	0.3%	-1.4%	-0.8%
Weight	0.5%	-2.2%	-2.4%	-17.4%	-14.5%	-1.2%
Center of Gravity						
x	14.1%	10.3%	11.3%	-17.0%	-13.5%	-5.2%
y	*	*	*	*	*	*
z	-10.9%	-10.8%	-8.1%	-1.7%	-2.7%	-8.7%

*Santschi assumes body symmetry for the location of the center of gravity along the y-axis.

and weight in the Santschi et al. (1963) study. A negative percentage means that the Chandler cadaver subjects had a lower value than the Santschi subjects. The differences in the locations of the center of gravity indicate a posterior movement of the center of gravity in the x-axis sitting position and a cephalad movement in the z-axes for both standing and sitting positions. Since the y-axis is the axis of symmetry, changes there are negligible. This latter observation can be verified in the results reported by Reynolds et al. (1975).

The standing x-axis location is difficult to measure on the living since variation in the dimension approaches the tolerance magnitude in most measurement systems. In the present instance, the apparent contradiction in the cadaver data with the changes which usually take place in embalmed cadavers is probably due to several differences between the two studies--back plane definition and subject head position are likely candidates. The average difference in percentage appears large but the average absolute difference is 1.2 cm (.47 in) which in most man-machine systems would probably be imperceptible.

Therefore, the cephalad shift in the location of the center of mass along the z-axis in zero gravity can be approximated by reducing the distance of the center of mass from vertex by a factor of 10%. The y-axis is best approximated by the assumption of symmetry, and the x-axis appears to be inconsistent. At present, the user must determine first the sensitivity of the system to shifts in the location of the center of mass along the x-axis before using cadaver data. In general, it would appear reasonable to assume that changes in segment position would affect the location more than tissue and fluid shifts but this is a problem that needs more extensive research.

Segments

The location of the center of mass in the limbs has traditionally been presented as a percent of link length. The torso presents a unique problem since it has been measured as a composite segment without attempting to separate it into individual links, an approach which does not satisfy the requirements of most three-dimensional models. Furthermore, the data contain no information on the changing location of the center of mass caused by fluid and organ shifts.

Most of the usable segment data have been collected from cadavers. Table 11 presents a summary of these data as a function of the ratio of segment length to distance of the center of mass along a longitudinal axis from some known landmark. These data have been used to generate the best estimate of the location of the center of mass given in Table 12. The coefficients for the x-axis (head and torso, primarily) should be multiplied by an anthropometric dimension measured from the back plane. The coefficients for the y-axis, which are always .5, assume segment symmetry. The coefficients for the z-axis should be multiplied by an anthropometric dimension measured from the most proximal joint in the limbs, suprasternale in the torso, and tragon-vertex height in the head. In all cases, the axis system is assumed to be orthogonal and relative to the geometric shape of the segment. (Coefficients were calculated using the average of data from the appropriate reports listed in Table 11.)

Clauser, McConville, and Young (1969) derived regression equations to estimate the center of mass of segments. These equations, which appear in Appendix B, Table 2, are derived from anthropometric input for the independent variables and locate centers of mass in two dimensions (in general, along the x- and z-axes). They have a relatively small standard error of the estimate. Data derived from these equations will be more appropriate for individualized models of the body if the individual's anthropometric information is available. In the event that individual dimensions are unknown the coefficients given in Table 12 can be used.

Segment Weight

A total of 65 cadavers and 273 living subjects have been used in mass distribution studies reported since 1860 but data on segment weights remain scarce. The little data that have been recorded are difficult to compare since definitions of segments differ. By and large, cadaver data are the most accurate since they can be measured directly. Extrapolation of segment weights for the living from embalmed cadavers assumes comparable densities and there are no data to support these assumptions under one-g conditions. Under zero-g conditions, however, observations made by the astronauts suggest that changes in the body are more analogous to the mass distribution measured in cadavers than to that indirectly measured on living subjects. Thus, the assumption of comparable density may provide reasonable estimates of the segment weights of astronauts in a zero-gravity environment.

TABLE 11
LOCATION OF THE CENTER OF MASS (CM) ¹

Segments	Chandler et al. (1975)			Clauser, McConville & Young (1969)			Becker (1972)			Dempster (1955)	Braune & Fischer (1889)
Head	x	y	z	x	y	z	x	y	z	In the sphenoid sinus approxi- mately 4mm beyond the anterior- inferior margin of the sella turcica.	Fossa Tarini ² Clivus
	0.02 (0.00)	-0.20 (-0.08)	2.67 (1.05)	-2.72 (-1.07)	Assuming symmetry	1.12 (0.44)	1.31 (0.52)	-0.10 (-0.04)	2.52 (0.99)		
Torso	CM-Suprasternale 21.20 (8.35)			CM-Suprasternale 22.02 (8.67)			NM ⁴			NM	Level of L1
	<u>Location of CM as a Percentage of the Distance from Proximal Joint Length to Total Link Length</u>										
Upper arm	50.92%			51.30%			NM			43.6%	46.8% 45.1 Lt.
Forearm	41.42			38.96			NM			43.0	Rt. 42.0 Lt.
Hand	51.75			18.02 ³			NM			50.6	5.6 cm ⁵ 5.4 cm ⁵ Lt.
Thigh	39.33			37.19			NM			43.3	44.2% 44.7 Lt.
Shank	41.75			37.05			NM			43.3	Rt. 42.2 Lt.
Foot	43.83			44.85			NM			43.8	42.9 43.9 Lt.

¹ Data given in centimeters with inches in parentheses.

² These locations are bony landmarks in the interior base of the skull that lie in the mid-sagittal plane approximately 2-3 cm in front of and slightly above the Trignon-Trignon axis.

³ Reported as CM-Meta III/Styilion-Meta III length.

⁴ Not measured.

⁵ Distance from proximal joint center.

TABLE 12
LOCATION OF BODY SEGMENTS' CENTER OF MASS

<u>Head</u>	x = Tragion to wall depth y = .5 bitragion breadth z = .17 tragion to vertex height
<u>Torso</u>	x = .44 waist depth at omphalion y = .5 waist breadth at omphalion z = .42 suprasternale to trochanterion
<u>Upper Arm</u>	x = Assume symmetry y = Assume symmetry z = .48 link length (Tables 1 & 3)
<u>Forearm</u>	x = Assume symmetry y = Assume symmetry z = .41 link length (Tables 1 & 3)
<u>Hand</u>	x = Assume symmetry of palm at z-axis location y = Assume symmetry of palm at z-axis location z = .51 palm length
<u>Thigh</u>	x = Assume symmetry y = Assume symmetry z = .41 link length (Tables 1 & 3)
<u>Shank</u>	x = Assume symmetry y = Assume symmetry z = .44 link length (Tables 1 & 3)
<u>Foot</u>	x = Assume symmetry of foot at z-axis location y = Assume symmetry of foot at z-axis location z = .44 foot length (from heel)

The weight of the body segments has been estimated in a number of ways. In 1957, Barter developed regression equations for predicting segment weight using total body weight as the independent variable from data reported by Braune and Fischer (1889), Fischer (1906), and Dempster (1955). Barter's equations, based on a sample of 12 cadavers, predicted the weight of seven segments and various combinations of segments. In order to update Barter's work with additional data and provide estimates for more individual segments, the equations in Table 13 were prepared. These equations are based on Barter's original sample with the addition of head and neck data

TABLE 13
PREDICTION EQUATIONS TO ESTIMATE SEGMENT WEIGHT BASED ON
REANALYSIS OF CADAVER DATA*

<u>Segment</u>	<u>Equation</u>	<u>R</u>	<u>Se_{est}</u>
Head	.0306 (TBW) + 2.46 (5.42)	.626	± .43 (.95)
Head & neck	.0534 (TBW) + 2.33 (5.14)	.726	± .60 (1.32)
Neck	.0146 (TBW) + .60 (1.32)	.666	± .21 (.46)
Head, neck & torso	.5940 (TBW) - 2.20 (4.85)	.949	± 2.01 (4.43)
Neck & torso	.5582 (TBW) - 4.26 (9.39)	.958	± 1.72 (3.79)
Total arm	.0505 (TBW) + .01 (.02)	.829	± .35 (.77)
Upper arm	.0274 (TBW) - .01 (.02)	.826	± .19 (.42)
Forearm & hand	.0233 (TBW) - .01 (.02)	.762	± .20 (.44)
Forearm	.0189 (TBW) - .16 (.35)	.783	± .15 (.33)
Hand	.0055 (TBW) + .07 (.15)	.605	± .07 (.15)
Total leg	.1582 (TBW) + .05 (.11)	.847	± 1.02 (2.25)
Thigh	.1159 (TBW) - 1.02 (2.25)	.859	± .71 (1.57)
Shank & foot	.0452 (TBW) + .82 (1.81)	.750	± .41 (.90)
Shank	.0375 (TBW) + .38 (.84)	.763	± .33 (.73)
Foot	.0069 (TBW) + .47 (1.04)	.552	± .11 (.24)

*Data given in kilograms with pounds in parentheses.

from Walker et al. (1973), and head, torso, arms, and legs data from Clauser et al. (1969) and Chandler et al. (1975). The segments are defined in accordance with the definitions provided in Appendix A and only those segments in each study which closely matched those definitions were used in the segment samples. Prediction equations for estimating segment weight were also developed by Clauser et al. (1969) in their study of 13 cadavers. These later equations utilize anthropometric dimensions as the independent variables and are thus more sensitive to individual variations. The Clauser et al. equations appear in Appendix B, Table 3.

A third method (referred to in the literature as the method of coefficients) makes use of percentages of total body weight to estimate segment weights. Most of the available information on this subject appears in Table 14 and has been further refined for use by engineers and modellers in Table 15. Studies by Liu and Wickstrom (1973) and Walker et al. (1973), who used eight cadavers in common, provided additional input for the torso and neck data which appears in Table 15. This table is for use in determining the mean population estimates of segment weights, and for determining the weight of torso segments not given by the regression equations. Table 16 provides estimates of segment weights for selected total body weights using the regression equations in Table 13 and the torso coefficients in Table 15.

TABLE 14
SEGMENTAL WEIGHT/BODY WEIGHT RATIOS FROM CADAVER STUDIES¹

Source	Harless (1960)	Braune & Fischer (1889)	Fischer (1906)	Dempster ² (1955)	Clauser et al. (1969)	Walker et al. (1973)	Chandler et al. (1975)	Mori & Yamamoto (1959)	Fujikawa (1963)
Sample	2M	3M	1M	8 M	13 M	20M	6M	3M	6M
Head and neck	7.6%	7.0%	8.8%	8.1%	7.3%	9.0%	6.1%	12.6%	8.2%
Trunk	44.2	46.1	45.2	49.7	50.7	-	52.2	53.7	53.6
Total arm	5.7	6.2	5.4	5.0	4.9	-	-	4.4	4.7
Upper arm	3.2	3.3	2.8	2.8	2.6	-	2.9	2.8	2.6
Forearm & hand	2.6	2.9	2.6	2.2	2.3	-	-	1.6	2.2
Forearm	1.7	2.1	-	1.6	1.6	-	1.7	1.1	1.4
Hand	0.9	0.8	-	0.6	0.7	-	0.6	0.5	0.8
Total leg	18.4	17.2	17.6	16.1	16.1	-	-	12.4	14.5
Thigh	11.9	10.7	11.0	9.9	10.3	-	10.2	7.4	9.4
Shank & foot	6.6	6.5	6.6	6.1	5.8	-	-	5.0	5.0
Shank	4.6	4.8	4.5	4.6	4.3	-	4.1	3.4	3.3
Foot	2.0	1.7	2.1	1.4	1.5	-	1.3	1.6	1.7
Total body weight ³	55.53 (122.44)	63.85 (140.79)	44.06 (97.15)	59.72 (131.68)	65.61 (144.67)	68.40 (150.82)	65.17 (143.70)	31.57 (69.61)	50.30 110.91

¹ Data presented for right side of body rather than average of right and left sides.

² Values adjusted by Clauser et al. 1969.

³ Data given in kilograms with pounds in parentheses.

TABLE 15
PERCENTAGE DISTRIBUTION OF TOTAL BODY WEIGHT ACCORDING TO
DIFFERENT SEGMENTATION PLANS

<u>Grouped Segments Percent of Total Body Weight</u>		<u>Individual Segments Percent of Grouped Segments Weight</u>	
Head and neck	= 8.4%	Head	= 73.8%
		Neck	= 26.2%
Torso	= 50.0%	Thorax	= 43.8%
		Lumbar	= 29.4%
		Pelvis	= 26.8%
Total arm	= 5.1%	Upper arm	= 54.9%
		Forearm	= 33.3%
		Hand	= 11.8%
Total leg	= 15.7%	Thigh	= 63.7%
		Shank	= 27.4%
		Foot	= 8.9%

There are two further methods available for estimating segment weights of living subjects, both of which incorporate an unknown error factor. Bernstein et al. (1931) developed a technique by which a segment weight could be estimated from a change in a lever arm moment due to the angular displacement of discrete body segments. This technique, however, assumes knowledge of the location of both the center of mass and joint center of rotation and these points are difficult to locate on the living subject. The method is further predicated on the assumption that center of mass is equivalent to center of volume and subsequent assessment of this assumption (by Clauser et al. 1969) revealed a systematic error in Bernstein's technique.

A sounder method is to calculate segment weights from segment volumes as percentages of total body volumes, correcting for density. The volume measurement technique described most frequently in the literature is underwater displacement, but other methods exist and the use of stereophotogrammetry is a promising new tool for measuring the mass distribution properties of the living body.

The majority of subjects used thus far have been males; only a few studies of females have ever been conducted. Presented in Table 17 are the data for segment volumes as percentages of total body volume for male cadavers and living subjects; comparable data for living female subjects appear in Table 18. It should be remembered that different segmentation planes for the upper arm and upper leg for cadavers and living subjects (see Figure 2) affect the results of calculations for the relevant limbs as well as for the torso. When the average segment volume percentages of

TABLE 16
SEGMENT WEIGHT DESIGN VALUES DERIVED FROM REGRESSION EQUATIONS IN TABLE 13*

<u>Segment</u>	45.37 (100)	54.45 (120)	63.52 (140)	72.59 (160)	81.67 (180)	90.74 (200)
TOTAL BODY WEIGHTS						
Head	3.87 (8.47)	4.12 (9.08)	4.40 (9.70)	4.68 (10.32)	4.95 (10.91)	5.23 (11.53)
Head & neck	4.75 (10.47)	5.24 (11.55)	5.72 (12.61)	6.20 (13.67)	6.69 (14.75)	7.17 (15.81)
Neck	1.27 (2.80)	1.40 (3.09)	1.53 (3.37)	1.66 (3.66)	1.80 (3.97)	1.93 (4.26)
Neck & torso	21.06 (46.44)	26.13 (57.62)	31.19 (68.77)	36.26 (79.95)	41.33 (91.13)	46.39(102.29)
Thorax**	9.30 (20.51)	11.62 (25.62)	13.94 (30.74)	16.26 (35.85)	18.58 (40.97)	20.90 (46.08)
Lumbar**	5.48 (12.08)	6.85 (15.10)	8.22 (18.13)	9.58 (21.12)	10.95 (24.14)	12.31 (27.14)
Pelvis**	5.01 (11.05)	6.26 (13.80)	7.50 (16.54)	8.75 (19.29)	10.00 (22.05)	11.25 (24.81)
Head, neck & torso	24.75 (54.57)	30.14 (66.46)	35.53 (78.34)	40.92 (90.23)	46.31(102.11)	51.70(114.00)
Total arm	2.30 (5.07)	2.76 (6.09)	3.21 (7.08)	3.67 (8.09)	4.13 (9.11)	4.59 (10.12)
Upper arm	1.23 (2.71)	1.48 (3.26)	1.73 (3.81)	1.98 (4.37)	2.23 (4.92)	2.48 (5.47)
Forearm & hand	1.05 (2.31)	1.26 (2.78)	1.47 (3.24)	1.68 (3.70)	1.89 (4.17)	2.10 (4.63)
Forearm	0.70 (1.54)	0.87 (1.92)	1.04 (2.29)	1.22 (2.69)	1.39 (3.06)	1.56 (3.44)
Hand	0.32 (0.71)	0.37 (0.82)	0.42 (0.93)	0.47 (1.04)	0.52 (1.15)	0.57 (1.26)
Total leg	7.23 (15.94)	8.66 (19.09)	10.10 (22.27)	11.53 (25.42)	12.97 (28.60)	14.40 (31.75)
Thigh	4.24 (9.35)	5.29 (11.66)	6.34 (13.98)	7.39 (16.29)	8.45 (18.63)	9.50 (20.95)
Shank & foot	2.87 (6.33)	3.28 (7.23)	3.69 (8.14)	4.10 (9.04)	4.51 (9.94)	4.92 (10.85)
Shank	2.08 (4.59)	2.42 (5.34)	2.76 (6.09)	3.11 (6.86)	3.45 (7.61)	3.79 (8.36)
Foot	0.78 (1.72)	0.85 (1.87)	0.91 (2.01)	0.97 (2.14)	1.03 (2.27)	1.10 (2.43)

*Data given in kilograms with pounds in parentheses.

**The weights of these segments are computed as a percentage of torso weight reported in Table 15.

TABLE 17
MALE SEGMENT VOLUME AS PERCENT OF TOTAL BODY VOLUME

Subjects	Cadaver			Living				
Studies	Clauser et al. (1969)	Chandler et al. (1975)	Average	Dempster (1955)	Cleaveland (1955)	Drilllis et al. (1966)	Katch & Waltman (1975)	Average
Head	5.4%							
Head & neck	7.0%				7.0%		7.4%	7.2%
Torso					48.1		46.2	47.2
Neck & torso	51.9	56.9	54.4%					
Upper arm	2.6	2.7	2.7	3.5%	3.1	3.5%		3.4
Forearm	1.5	1.5	1.5	1.5	1.6	1.7		1.6
Upper & forearm	4.1	4.2	4.2	5.0	4.7	5.2	5.6	5.1
Hand	0.6	0.5	0.6	0.6	0.5	0.6	0.7	0.6
Total arm	4.7	4.7	4.7	5.6	5.2	5.8	6.3	5.7
Thigh	10.3	9.4	9.9	14.2	11.2	9.2		11.5
Shank	4.2	3.6	3.9	4.9	4.4	4.1		4.5
Thigh & shank	14.5	13.0	13.8	19.1	15.6	13.3	15.2	15.8
Foot	1.4	1.1	1.3	1.4	1.3	1.3	1.7	1.4
Total leg	15.9	14.1	15.0	20.5	16.9	14.6	16.9	17.2
Total body	100.1%	99.9%	100.0%		99.3%		100.0%	
N	13	6	-	39	12	11	24	
Stature*	172.7	172.1	172.4	174.5	175.8	176.0	176.9	175.8
Weight*	65.6	65.17	65.4	75.6	71.5	73.42	76.2	73.9
Age	49.3	54.3	51.9	20.6	27.2	20.8	21.2	22.5
TB volume*	62.99	69.61	66.3	71.32**	66.73	69.26**	71.89**	69.8

*Stature is reported in centimeters, weight in kilograms and total body volume in liters.

**Total body volume computed as weight ÷ 1.06.

TABLE 18
FEMALE SEGMENT VOLUME AS PERCENT OF TOTAL BODY VOLUME

	Katch & Weltman (1975)	Kjeldsen (1972)
Head & neck	8.3%	8.8%
Torso		(50.7%)
Upper torso		16.4%
Lower torso		34.3%
Upper arm		2.8%
Lower arm		1.4%
Upper & lower arm	4.5%	(4.2%)
Hand	0.6%	0.5%
Thigh		9.4%
Thigh & shank	15.4%	(14.4%)
Foot	1.6%	1.2%
N	23	12

total body volume are compared with the percentages for weight, the differences are small, reflecting the close correlation between volume and weight. Thus, to estimate segment weight, the percentages from either Table 17 or Table 18 can be used. To estimate segment volume, regression equations appearing in Appendix B, Table 4 can also be used.

If segment volume is available for an individual or for a population, the density data in Table 19 will provide the necessary values for estimating weight from volume. These values are based on cadaveric data and have the same bias which is present in the actual segment weights of cadavers. Therefore, whether segment weights for astronauts are estimated via regression equations or measured segment volume, the engineer must assume that cadaver data is only an approximation of these properties in the living body. The accuracy with which these data reflect living body weight distribution is essentially unknown, but they are the best approximations available.

Moments of Inertia

This section will serve as a guide to the inertial properties of the whole body and its segments. Its purpose is to present the available empirical data for estimating moments of inertia and to present methods of estimating these properties for specific populations.

The inertial properties of the whole body and its segments have been reported in a variety of ways: as moments of inertia; as a momental ellipsoid of inertia; and as an inertia tensor. All three describe the

TABLE 19
SEGMENT DENSITY FOR MALE CADAVERS
(Values in grams/cm³)

	Dempster (1955)	Clauser et al. (1969)	Chandler et al. (1975)	Average
Head			1.06	1.06
Head & neck	1.11	1.07		1.09
Torso				
Neck & torso		1.02	0.85	0.94
Head, neck, & torso	1.03	1.03		1.03
Upper arm	1.07	1.06	1.00	1.04
Lower arm	1.13	1.10	1.05	1.09
Hand	1.16	1.11	1.08	1.12
Thigh	1.05	1.04	1.02	1.04
Shank	1.09	1.08	1.07	1.08
Foot	1.10	1.08	1.07	1.08

inertial properties of an individual but are based on different assumptions or data analysis methods.

Moments of inertia are defined about an axis of rotation which, in most studies, is defined as passing through the center of gravity, but occasionally is defined as passing through an estimated joint center of rotation. All the moments reported in this section are about axes passing through centers of gravity. In the studies of living subjects, the measured moments of inertia are reported about three orthogonal axes defined by the researcher. In recent studies using cadaver specimens, moments about six or more axes were measured in order to determine an inertial tensor which was used to derive the principal moments of inertia about the principal axes of inertia.

As with other mass distribution properties, data on the whole body are obtained primarily from measurements of living subjects and data on segments come primarily from measurements of cadavers. A comparison has been made on the following pages which will clarify the differences between methods used in studies of cadavers and that used in the study of living subjects.

Whole Body

Measurements of whole body moments of inertia are position-dependent data since they describe the mass distribution in a particular position assumed by the subject during the measurement procedure. As soon as any

of the segments change position, the magnitude and direction of the moments of inertia are changed. The only reasonable approach for data on the whole body is to measure moments of inertia for common positions of the body. Three such studies, covering a range of positions for the moments of inertia relative to an inertial "anatomical" axis system located at the center of gravity of the living body, have been undertaken.

The first direct measures of moments of inertia of the whole body were made by Santschi et al. (1963) on 66 subjects representative of the U.S. Air Force flying personnel. Using a compound pendulum with the body in the eight positions depicted in Figure 9, investigators measured three moments of inertia about three axes passing through the center of gravity of the body. The data, summarized in Table 20, give the moments of inertia for U.S. males and include regression equations which predict the moments of inertia about an "anatomical" axis system defined by the intersection of the three cardinal anatomical planes with an origin at the center of gravity for the whole body (See Figure 1).

Table 21 presents values computed from the regression equations in Table 20 for small, medium and large white males in the standing, sitting and relaxed (weightless) positions. These estimates are appropriate for the U.S. white male population projected for 1985 as are the following data from DuBois.

Using the same measurement techniques, DuBois et al. (1964), enlarged on the Santschi study by measuring three moments of inertia about the same axes on 19 male subjects wearing full-pressure suits. The subjects assumed only two positions (sitting and relaxed) but were measured in three dress conditions: nude, unpressurized suit, and pressurized suit (See Figure 10). The suit sizes ranged from small-regular to extra-large-long. Table 22 presents the summary statistics and regression equations and Table 23 contains values computed from the regression equations in Table 22.

There has been one French study in which the inertial properties of living subjects were measured. Ignazi et al. (1972) measured three moments of inertia on eleven standing male subjects using a method similar to that used in the U.S. studies. Table 24 presents the summary statistics for height, weight, and the moments of inertia for the x-, y- and z-axes as well as multiple regression equations for predicting the moments of inertia and center of mass from anthropometric dimensions. This study represents the only source of whole body inertial information on European subjects.

The above-described studies are based on the assumption that the "anatomical" axis system (as depicted in Figure 1) reasonably approximates the principal axes of inertia. The basic difference between them is that the "anatomical" axis system is a hypothetical construction imposed on the body by the investigator while the principal axes of inertia are inherent in the body or its parts. The former is unaffected by the dynamics of the body while the latter change as the body configuration and mass distribution change in time and space.

TABLE 20
MEANS, STANDARD DEVIATIONS, AND REGRESSION EQUATIONS FOR
WHOLE BODY MOMENTS OF INERTIA FROM SANTACHI ET AL. (1963)

	Axis	Moment of Inertia ¹		$R_{1.5V}^2$	Se _{est.}	I ₀ Regression Equations ³
		Mean	S.D.			
1. Standing	x	115.0	19.3	0.98	4.18	3.77S + 0.512W - 232.0
	y	103.0	17.9	0.96	5.27	3.43S + 0.460W - 212.0
	z	11.3	2.2	0.93	0.84	-0.098S + 0.112W - 0.604
2. Standing, arms over head	x	152.0	26.1	0.98	5.63	5.36S + 0.652W - 328.0
	y	137.0	25.3	0.96	6.89	5.34S + 0.589W - 332.0
	z	11.1	1.9	0.89	0.87	-0.085S + 0.094W + 1.4
3. Spread eagle	x	151.0	27.1	0.98	4.90	5.63S + 0.677W - 353.0
	y	114.0	21.3	0.96	6.24	4.30S + 0.516W - 270.0
	z	36.6	7.9	0.93	2.82	1.52S + 0.191W - 101.0
4. Sitting	x	61.1	10.3	0.92	4.01	1.43S + 0.322W - 91.6
	y	66.6	11.6	0.92	4.51	2.26S + 0.268W - 135.0
	z	33.5	5.8	0.97	1.45	0.76S + 0.201W - 52.8
5. Sitting, forearms down	x	62.4	9.7	0.91	3.98	1.29S + 0.309W - 78.7
	y	68.1	12.0	0.92	4.67	2.05S + 0.321W - 127.0
	z	33.8	5.9	0.97	1.36	0.765S + 0.206W - 53.7
6. Sitting, thighs elevated	x	39.1	6.0	0.89	2.79	0.543S + 0.212W - 33.8
	y	38.0	5.8	0.77	3.66	0.434S + 0.180W - 22.2
	z	26.3	5.1	0.92	2.00	0.328S + 0.204W - 30.4
7. Mercury configura- tion	x	65.8	10.3	0.93	3.75	1.57S + 0.308W - 94.3
	y	75.2	14.0	0.94	4.96	2.85S + 0.318W - 175.0
	z	34.2	5.6	0.96	1.64	0.668S + 0.197W - 45.0
8. Relaxed (weightless)	x	92.2	13.3	0.96	3.71	1.77S + 0.452W - 106.0
	y	88.2	13.3	0.94	4.54	2.43S + 0.352W - 139.0
	z	35.9	5.4	0.96	1.54	0.776S + 0.176W - 47.2

¹ Values for I₀ are given in lb.in.sec.². For conversion to other units, see Appendix C.

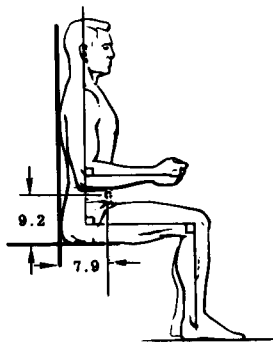
² Multiple correlation coefficient of stature and weight with the independent variables.

³ (Stature) in inches
(Weight) in pounds

TABLE 21
WHOLE BODY MOMENTS OF INERTIA FOR MALE WHITES COMPUTED FROM TABLE 20*

		Small: 5th %ile	Medium: 50th %ile	Large: 95th %ile
		168.2 cm. (66.2 in.) 65.2 kg. (143.7 lb.)	178.4 cm. (70.2 in.) 81.5 kg. (180.0 lb.)	188.6 cm. (74.3 in.) 97.7 kg. (215.3 lb.)
Standing	x	1b.-in.sec ² gm-cm ² (x10 ⁶)	1b.-in.sec. ² gm-cm ² (x10 ⁶)	1b.-in.sec. ² gm-cm ² (x10 ⁶)
	y	91.148 103.065	124.814 141.132	158.345 179.047
	z	81.168 91.780	111.586 126.175	141.887 160.438
		9.003 10.180	12.676 14.333	16.228 18.350
Sitting	x	49.337 55.787	66.746 75.473	83.976 94.955
	y	53.124 60.070	71.892 81.291	90.618 102.466
	z	26.396 29.847	36.732 41.534	49.943 56.473
Relaxed	x	76.126 86.079	99.164 112.638	122.827 138.886
	y	72.448 81.920	94.946 107.359	117.335 132.676
	z	29.462 33.314	38.955 44.048	48.350 54.671

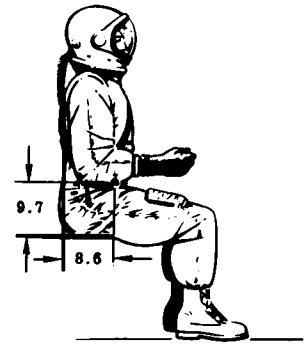
*For conversion to other units, see Appendix C.



Nude

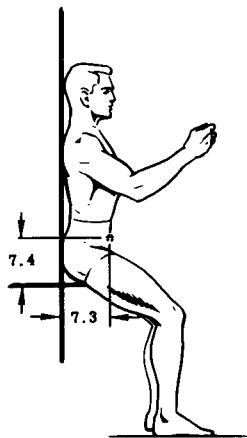


Unpressurized

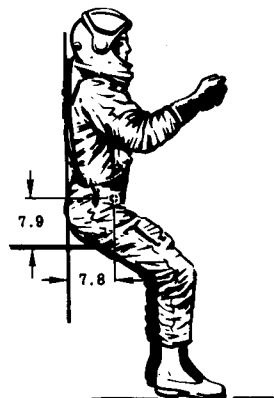


Pressurized

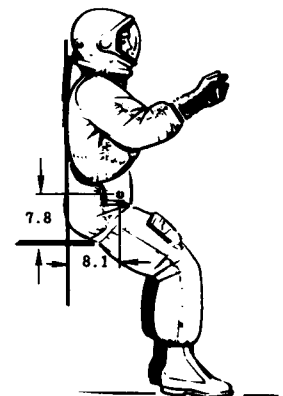
1. Sitting



Nude



Unpressurized



Pressurized

2. Relaxed (Weightless)

Figure 10. Mean centers of gravity in nude and suited subjects (from DuBois et al., 1964).

TABLE 22
MEANS, STANDARD DEVIATIONS, AND REGRESSION EQUATIONS FOR
WHOLE BODY MOMENTS OF INERTIA FROM DUBOIS ET AL. (1964)

	Axis	Moment of Inertia ¹		R _{1,sw} ²	S _{est.}	I _o Regression Equation ³
		Mean	S.D.			
Sitting Nude	x	56.3	8.22	0.95	2.67	1.59S + 0.317W - 105.0
	y	66.5	9.98	0.91	4.07	2.10S + 0.344W - 135.0
	z	28.3	5.10	0.97	1.17	0.923S + 0.212W - 70.4
	x	67.5	9.16	0.93	3.42	1.82S + 0.337W - 114.0
	y	82.8	11.30	0.97	2.77	2.96S + 0.362W - 181.0
	z	33.6	5.72	0.97	1.47	1.09S + 0.229W - 79.5
	x	68.8	8.70	0.93	3.24	2.06S + 0.281W - 120.0
	y	82.4	11.30	0.94	3.79	2.54S + 0.389W - 157.0
	z	34.0	5.72	0.96	1.53	1.07S + 0.230W - 78.1
Relaxed (Weightless) Nude	x	99.2	14.20	0.97	3.30	2.88S + 0.556W - 191.0
	y	89.8	15.20	0.95	4.60	4.04S + 0.461W - 265.0
	z	31.2	5.04	0.94	1.75	0.567S + 0.231W - 46.0
	x	118.0	15.30	0.95	4.62	3.19S + 0.574W - 197.0
	y	114.0	15.00	0.96	4.38	3.59S + 0.506W - 217.0
	z	36.2	5.03	0.96	1.33	0.801S + 0.217W - 54.8
	x	118.0	15.20	0.97	3.93	3.42S + 0.550W - 208.0
	y	114.0	15.70	0.96	4.44	4.18S + 0.482W - 254.0
	z	36.1	4.85	0.96	1.36	0.720S + 0.214W - 48.7

¹ Values for I_o are given in lb.in.sec.². For conversion to other units, see Appendix D.

² Multiple correlation coefficient of stature and weight with the independent variables.

³ S (Stature) in inches.

W (Weight) in pounds.

TABLE 23
WHOLE BODY MOMENTS OF INERTIA FOR MALE WHITES COMPUTED FROM TABLE 22*

		Small: 5th %ile		Medium: 50th %ile		Large: 95th %ile	
		168.2 cm. (66.2 in.)	62.104	178.4 cm. (70.2 in.)	84.174	188.6 cm. (74.3 in.)	106.067
		65.2 kg. (143.7 lb.)	75.744	81.5 kg. (180.0 lb.)	103.998	97.7 kg. (215.3 lb.)	132.177
			28.914		43.247		57.445
		1b.-in.sec. ²	gm-cm ² (x10 ⁶)	1b.-in.sec. ²	gm-cm ² (x10 ⁶)	1b.-in.sec. ²	gm-cm ² (x10 ⁶)
Sitting	Unpressurized x	54.911	62.104	74.424	84.174	93.782	106.067
	y	66.971	75.744	91.952	103.998	116.867	132.177
	z	25.565	28.914	38.238	43.247	50.791	57.445
	Pressurized x	56.752	64.187	75.192	85.042	93.557	105.813
	y	67.047	75.830	91.328	103.292	115.474	130.601
	z	25.785	29.163	38.414	43.446	50.920	57.591
Relaxed	Unpressurized x	96.662	109.325	130.258	147.030	163.599	185.030
	y	93.370	105.601	126.098	142.617	158.679	179.466
	z	29.409	33.262	40.490	45.794	51.434	58.172
	Pressurized x	97.439	110.204	131.084	148.256	164.521	186.073
	y	91.979	104.028	126.196	142.728	160.349	181.355
	z	29.716	33.609	43.364	49.045	50.870	57.534

*For conversion to other units, see Appendix C.

TABLE 24
MEANS, STANDARD DEVIATIONS AND REGRESSION EQUATIONS FOR WHOLE
BODY MOMENTS OF INERTIA FROM IGNAZI ET AL. (1972)

Axis ¹	Moment of Inertia ²		$R_{1 \cdot SW}^3$	$Se_{est.}$	I_o Regression Equation ⁴
	Mean	S.D.			
x	11.51	1.99	.980	0.396	$0.136W + 0.119S - 18.874$
y	12.38	2.03	.985	0.351	$0.106W + 0.172S - 25.211$
z	1.12	0.29	.963	0.079	$0.033W - 0.006S - 2.135$

¹ See axis system definition in Table 9.

² Values are given in kg.m². For conversion to other units, see Appendix D.

³ Multiple correlation coefficient of stature and weight with the independent variables.

⁴ S (Stature) in centimeters

W (Weight) in kilograms

Chandler et al. (1975) conducted the first study to determine the principal moments of inertia about the principal axes of inertia in the whole body. The subjects were six embalmed cadavers. The principal moments of inertia are presented in Table 25 relative to a right-handed orthogonal axis system located at the whole body center of gravity. These moments were determined about the principal axes according to a technique described by Winstandley et al. (1968) and further discussed in the Chandler et al. report.

Inertial data from the Chandler study can be used to examine the assumption that the "anatomical" axis system (about which the three previous investigators measured their data) approximates the principal axes of inertia. This "anatomical" axis system has been treated as an inertial frame of reference defined in the standard anatomical position. The axis system about which the principal moments of inertia in the Chandler study were determined, defines the momental ellipsoid of inertia (Synge and Griffith, 1942). Table 26 presents a comparison of the Chandler data with data from the Santschi study for subjects individually matched for height and weight.

In general, the percentage differences are small for the principal moments of inertia in the standing position indicating that the "anatomical" axis system closely approximates the principal axes of the momental ellipsoid of inertia in that position. It will be noted that the z-axes in the sitting position are significantly different. These differences are attributed to the displacement of the appendages away from the cardinal anatomical planes. As a general rule for symmetrical displacements of the appendages relative to the torso, moments of inertia about the x-axis and y-axis will most closely approximate the principal moments of inertia measured about the "anatomical" axis. The z-axis will have the poorest approximation since it is the major axis of the ellipsoid and hence the most sensitive.* The two studies by Chandler et al. (1975) and Becker (1972) in which moments of inertia were measured about principal axes result in more reliable data except for unresolved differences between them concerning head data.

All available data were measured under one-g conditions and therefore incorporate the effect of gravity on the tissues and fluids of the body. Although some raw data on inertial properties under zero-g conditions have been collected, they have not been analyzed, so there are, as yet, no guidelines for adjusting values for moments of inertia in the zero-g environment.

*The magnitude of the axes in a momental ellipsoid is given by the square root of the inverse of a moment of inertia. Therefore, for a typical ellipsoid, the major axis passes through the centroid and a point on the surface defined by a tangent to the greatest rate of curvature. Therefore the major axis is the most sensitive to minor changes in the mass distribution of the body.

TABLE 25
PRINCIPAL MOMENTS OF INERTIA FROM CHANDLER ET AL. (1975)

Subject	Standing			Sitting			X	SD
	1	2	3	4	5	6		
Age	65	45	47	58	61	50	54.3	7.4
Weight*	58.7 (129.43)	76.15 (167.91)	89.15 (196.58)	50.62 (111.62)	58.08 (128.07)	58.34 (128.64)	65.17 (143.70)	13.21 (29.13)
Stature*	167.8 (66.06)	181.7 (71.54)	174.2 (68.58)	175.9 (69.25)	168.8 (66.46)	164.5 (64.76)	172.15 (67.78)	5.75 (2.26)
	Principal Moments of Inertia ($\times 10^3 \text{ gm} - \text{cm}^2$)							
I_{xx} (Standing) (Seated)	98,807 ---	150,886 ---	169,127 ---	---	---	---	133,967.0 67,306.7	45,391.4 3,087.0
I_{yy} (Standing) (Seated)	89,223 ---	125,580 ---	141,888 ---	---	---	---	118,897.0 65,516.7	24,611.9 4,161.4
I_{zz} (Standing) (Seated)	11,644 ---	17,424 ---	22,388 ---	---	---	---	17,152.0 14,885.0	4,908.7 2,864.1

*Data given in kilograms and centimeters with pounds and inches in parentheses.

TABLE 26
COMPARISON OF MOMENTS OF INERTIA BETWEEN CHANDLER ET AL. (1975)
AND SANTSCHI ET AL. (1963)

Subject #	<u>Standing</u>				<u>Sitting</u>	
	1/19	2/1	3/17	4/26	5/16	6/39
Ix*	-4.05%	0.84%	7.04%	14.67%	4.15%	10.76%
Iy*	-2.69%	-7.17%	2.82%	-3.03%	-5.16%	-10.54%
Iz*	18.10%	14.94%	21.42%	-183.33%	-91.95%	-107.59%

*Deviation as percent of cadaver value.

Segments

Table 27 presents a summary of the data from four cadaver studies. Although the sample sizes are too small to permit definitive conclusions for the population, these are the only data of their kind available and may be used with caution. It should also be noted when using this table that some differences between the samples are attributable to differing definitions of the segments and the resultant variations in segment mass.

As can be observed from the table, Chandler et al. (1975) and Becker (1972) measured the principal moments of inertia about three principal axes of inertia. The results of both studies confirm that, for our purposes, moments of inertia about the "anatomical" axes closely approximate the principal moments of inertia determined about the principal axes of inertia for body segments.

For the modeler, there are three approaches which can be used to predict the principal moments of inertia of body segments. Table 28 presents the first and simplest approach by providing coefficients from the data in the Chandler study for the radii of gyration ($K = I/M$) expressed as a ratio, or percentage, of segment length. To estimate the radius of gyration, multiply the segment length (or link length) by the appropriate coefficient found in Table 28. The resulting product is multiplied by the appropriate segment weight (see Table 13) to obtain the principal moments of inertia for each segment. Table 29 presents some sample calculations for small (5th percentile), medium (50th percentile) and large (95th percentile) 1985 males.

The torso in Table 28 corresponds to the segmentation plan followed in the Chandler study which combined the neck, thorax, abdomen and pelvis segments into one. Geometric models, based on segment weight estimates in Table 15, can be used to calculate inertial properties of these four segments.

TABLE 27¹
SEGMENT MOMENTS OF INERTIA (10^{-3} gm-cm²) THROUGH THE CENTER OF MASS

	Chandler, et al. (1975)			Becker (1972)			Dempster (1955) I_{x-y} ²	Braune & Fischer (1972)		
	I_{xx}	I_{yy}	I_{zz}	I_{xx}	I_{yy}	I_{zz}		Cadaver 1 I_{x-y}	Cadaver 1 I_{x-y}	Cadaver 2 I_z
Head	174.0	164.4	202.9	198.5	221.0	133.8	NM ³	---	179.94	---
Torso	16,193.7	10,876.3	3,785.1		NM ³		NM	---	5,574.6	---
Upper arm										
Rt.	135.0	132.7	20.1		NM		142.0	101.0	75.56	9.66
Lt.	152.1	137.7	22.8		NM		139.0	121.0	75.98	9.40
Forearm										
Rt.	66.9	64.5	8.8		NM		56.0	130.0 ⁴	121.5 ⁴	8.45 ⁴
Lt.	64.7	63.0	8.6		NM		55.0	142.0 ⁴	152.2 ⁴	8.85 ⁴
Hand										
Rt.	7.54	6.15	2.15		NM		5.0			
Lt.	6.84	5.57	1.79		NM		4.5			
Thigh										
Rt.	1137.3	1157.9	224.9		NM		1100.0	684.0	589.1	100.61
Lt.	1151.4	1221.2	212.5		NM		1080.0	818.0	628.4	100.02
Shank										
Rt.	391.3	392.8	29.1		NM		430.0	257.0	173.68	20.15
Lt.	394.9	389.6	28.6		NM		416.0	271.0	176.37	17.58
Foot										
Rt.	32.10	31.08	7.04		NM		31.0	36.0	34.785	35.093
Lt.	33.13	30.43	7.54		NM		29.0	38.0	32.433	35.433
Head & neck	---	---	---	359.1	452.2	257.6	294.0	---	---	---
Head & torso	---	---	---	---	---	---	18,400.0	9,417.00	10,571.5	---

¹ For conversion to other units, see Appendix D.

² This axis is undefined except to say that it is perpendicular to the long axis and passes through the center of mass.

³ NM = Not Measured.

⁴ Forearm and hand measured together.

TABLE 28
THE RADIUS OF GYRATION (K) AS A PERCENT OF SEGMENT LENGTH

		<u>L</u>	<u>K/L</u>
Head	x	Head length	31.6%
	y		30.9%
	z		34.2%
Torso	x	Torso length	43.0%
	y	(Suprasternale hgt.	35.2%
	z	-trochanterion hgt.)	20.8%
Upper arm	x	Acromion-radiale l.	26.1%
	y		25.4%
	z		10.4%
Forearm	x	Radiale-stylian l.	29.6%
	y		29.2%
	z		10.8%
Hand	x	Hand breadth	50.4%
	y		45.6%
	z		26.6%
Thigh	x	Trochanterion hgt.	27.9%
	y	-fibular hgt.	28.4%
	z		12.2%
Shank	x	Fibular hgt.	28.2%
	y		28.2%
	z		7.6%
Foot	x	Foot length	26.1%
	y		24.9%
	z		12.2%

A second method of predicting the principal moments of inertia is to use regression equations based on body weight, segment weight or segment volume. These equations were computed in the Chandler study and are given in Appendix B, Table 5. The same segmentation plan as that used in Table 28 must be followed but the equations are based on a slightly different set of independent data.

A third method by which a design engineer can estimate the principal moments of inertia of body segments is to use geometric models. There are several current models which utilized geometric estimates, including those developed by Bartz and Gianotti (1973), Hanavan (1964) and Tieber and Lindemuth (1965). These models share some common assumptions which are well known but are not inherent in the two previously reported methods. First,

TABLE 29
SEGMENT MOMENTS OF INERTIA AS COMPUTED FROM THE COEFFICIENTS IN TABLE 28

		Small: 5th %ile		Medium: 50th %ile		Large: 95th %ile	
		168.2 cm. (66.2 in.) 65.2 kg. (143.7 lb.)		178.4 cm. (70.2 in.) 81.5 kg. (180.0 lb.)		188.6 cm. (74.3 in.) 97.7 kg. (215.3 lb.)	
		kg-cm^2	lb.in.^2	kg-cm^2	lb.in.^2	kg-cm^2	lb.in.^2
Head	x	156.9	0.139	195.7	0.173	240.3	0.213
	y	150.0	0.133	187.2	0.166	229.7	0.203
	z	183.8	0.163	229.3	0.203	281.5	0.249
Torso	x	14604.0	12.916	20219.2	17.882	21837.2	19.313
	y	9786.5	8.655	13549.2	11.983	14632.9	12.941
	z	3417.5	3.022	4731.0	4.184	5109.3	4.519
Upper arm	x	111.1	0.098	166.0	0.147	233.7	0.207
	y	99.9	0.088	157.2	0.139	221.3	0.196
	z	17.6	0.016	26.3	0.023	37.1	0.033
Forearm	x	57.7	0.051	88.5	0.078	127.6	0.113
	y	56.1	0.050	86.1	0.076	124.2	0.110
	z	7.7	0.007	11.8	0.010	17.0	0.015
Hand	x	7.4	0.007	10.4	0.009	14.3	0.013
	y	6.1	0.005	8.5	0.008	11.7	0.010
	z	2.1	0.002	2.9	0.003	4.0	0.003
Thigh	x	1123.9	0.994	1666.6	1.474	2334.9	2.065
	y	1164.5	1.030	1726.8	1.527	2419.5	2.140
	z	214.9	0.190	318.7	0.282	446.5	0.395
Shank	x	369.3	0.327	534.3	0.473	736.9	0.652
	y	369.3	0.327	534.3	0.473	736.9	0.652
	z	26.8	0.024	38.8	0.034	53.5	0.047
Foot	x	40.1	0.035	52.1	0.046	66.6	0.059
	y	36.5	0.032	47.4	0.042	60.6	0.054
	z	8.8	0.008	11.4	0.010	14.5	0.013

geometric models assume rigid homogeneous bodies of unknown density usually estimated to be 1.0. Second, they assume the shape of these bodies to be best approximated by symmetrical geometric shapes. As a consequence, they further assume that the principal "geometric" axes are the same as the principal "inertial" axes. Based on empirical data collected thus far, the last assumption appears to have some validity although it must be pointed out that the only comparison presently possible is between data collected on six embalmed cadavers and the geometric models.

The first two methods described above are derived from directly measured data which suggests that they are more accurate and more individualized than the older method which relies on geometric models. However, computer programs, which do exist for the geometric models, have not yet been written for the newer empirical equations, so the ultimate decision concerning which method to employ must be made by the user who will examine his requirements and select accordingly.

The reader of this chapter will have noted, perhaps with some impatience, the number of reservations and cautionary statements surrounding much of the material presented here, the number of alternative approaches offered and the frequency with which the lack of hard data has been pointed out. This is an inevitable consequence of any attempt to assemble a usable and up-to-date body of knowledge in an area in which verified data are still so sparse and in which so much research and validation remains to be done. We are still on the frontiers of understanding the inertial properties of the human body.

Nevertheless, despite the limitations and deficiencies of the published data, material in this chapter provides the user for the first time with a means of estimating the mass distribution properties of the human body from empirical data rather than solely from the traditional geometrical models. This is a major step toward a fuller understanding of the biomechanical behavior of the human body.

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APPENDIX A
THE ANATOMICAL FRAMEWORK

Joint Centers of Rotation and Linkage and Axis Systems
for Body Segments

1. Joint Centers of Rotation

Head/Neck	-Midpoint of the interspace between the occipital condyles and the first cervical vertebra.
Neck/Thorax	-Midpoint of the interspace between the 7th cervical and 1st thoracic vertebral bodies.*
Thorax/ Lumbar	-Midpoint of the interspace between the 12th thoracic and 1st lumbar vertebral bodies.*
Lumbar/Sacral	-Midpoint of the interspace between the 5th lumbar and 1st sacral vertebral bodies.*
Sternoclavicular	-"Midpoint position of the palpable junction between the proximal end of clavicle and the sternum at the upper border (jugular notch) of the sternum." (Dempster, p. 123, 1955)
Claviscapular	-"Midpoint of a line between the coracoid tuberosity of the clavicle (at the posterior border of the bone) and the acromioclavicular articulation (or the tubercle at the lateral end of the clavicle); the point, however, should be visualized as on the underside of the clavicle."(Dempster, p. 123, 1955)
Glenohumeral	-"Midregion of the palpable bony mass of the head and tuberosities of the humerus; with the arm abducted about 45° relative to the vertebral margin of the scapula, a line dropped perpendicular to the long axis of the arm from the outermost margin of the acromion will approximately bisect the joint." (Dempster, p. 125, 1955)

*These locations are defined relative to the last and first vertebrae of each of the major anatomical vertebrae groups. Thus, there are occasionally missing or additional vertebrae which would not change the functional definition of these links.

Elbow	- "Midpoint on a line between (1) the lowest palpable point the medial epicondyle of the humerus, and (2) a point 8mm above the radiale (radiohumeral junction)." (Dempster p. 125, 1955)
Wrist	- "On the palmar side of the hand, the distal wrist crease at the palmaris longus tendon, or the midpoint of a line between the radial styloid and the center of the pisiform bone; on the dorsal side of the hand, the palpable groove between the lunate and capitate bones, on a line with metacarpal bone III." (Dempster p. 125, 1955)
Hip	- "(Lateral aspect of the hip). A point at the tip of the femoral trochanter 0.4 inch anterior to the most laterally projecting part of the femoral trochanter." (Dempster, p. 125, 1955)
Knee	- "Midpoint of a line between the centers of the posterior convexities of the femoral condyles." (Dempster, p. 125, 1955)
Ankle	- "Level of a line between the tip of the lateral malleolus of the fibula and a point 5mm distal to the tibial malleolus." (Dempster, p. 125, 1955).

2. Body Segments: Recommended Links and Axis Systems

Head

Link: The straight line between the occipital condyle/C1 interspace center and the center of mass of the head.

Axis System: Formed relative to the Frankfort Plane which is the standard anthropometric measurement position parallel to the transverse (XY) plane. The Frankfort Plane (XY) is established by left infra-orbitale and right and left ear holes. The YZ plane will be perpendicular to the XY plane passing through the left and right ear holes. The XZ-plane will be constructed as a normal to the XY and YZ -planes passing through nasion in the mid-sagittal plane. Thus, the point of origin will be at the mid-point of the biporation axis. The +X-axis will pass anteriorly along the intersection of the XZ- and XY-planes; the +Y axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes. This axis closely approximates the system used in Chandler et al. (1975).

Neck

Link: The straight line between the occipital condyle/C1 and C7/T1 vertebral interspace joint centers.

Axis-System: Formed relative to the mid-sagittal plane (XZ) defined by the occipital condyle/C1 and C7/T1 vertebrae interspace centers and the most anterior chin/neck intersect point. The YZ-plane will be constructed as a perpendicular to the XZ-plane passing through the occipital condyle/C1 and C7/T1 vertebral interspace centers. The XY-plane will be constructed as a normal to the XZ and YZ-planes passing through the most anterior chin/neck intersect point. Thus, the point of origin will be at the intersection of the three planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Torso

Link: The straight line distance from the occipital condyle/C1 interspace joint center to the midpoint of a line passing through the right and left hip joint center.

Axis System: Formed relative to the mid-sagittal (XZ) plane defined by suprasternale and occipital condyle/C1 interspace and the hip joint centers midpoint. The YZ-plane will be formed as a perpendicular to the mid-sagittal plane passing through the occipital condyle/C1 interspace and the hip joint centers midpoint. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through suprasternale. Thus, the point of origin will be close to the C7/T1 interspace of the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection passing through the hip knee joint centers of rotation. The XY- plane will be constructed as a normal to the XZ- and YZ-planes passing through the anterior surface point. Thus, the point of origin will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Thorax

Links: Thoraco-sternum - A closed linkage system composed of three links. The right and left transthorax are straight line distances from the C7/T1 interspace to the right and left sternoclavicular joint centers of rotation. The transternum link is a straight line distance between the right and left sternoclavicular joint centers of rotation. Clavicular - The straight line between the sternoclavicular and the claviscapular joint centers. Scapular - The straight line between the claviscapular and glenohumeral joint centers. Thoracic - The straight line between C7/T1 and T12/L1 vertebral body interspace joint centers.

Axis System: Formed relative to the mid-sagittal (XZ) plane defined by suprasternale and center of the vertebral body interspaces of C7/T1 and T12/L1. The YZ-plane will be formed as a perpendicular to the mid-sagittal plane passing through the C7/T1 interspace. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through the C7/T1 interspace. Thus, the point of origin will be at the C7/T1 interspace. The +X-axis will pass anteriorly along the intersection of the XY- and YZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Lumbar

Link: The straight line between the T12/L1 and L5/S1 vertebrae interspace joint centers.

Axis System: Formed relative to the mid-sagittal plane (XZ) defined by the T12/L1 and L5/S1 joint centers and umbilicus. The YZ-plane will be formed perpendicular to the XZ-plane passing through the T12/L1 and L5/S1 joint centers. The XY-plane will be formed as a normal to the XZ- and YZ-planes passing through L5/S1. Thus, the point of origin will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Pelvis

Links: The pelvis is treated as a closed-loop linkage system composed of three links. The right and left iliopelvic links are straight lines between the L5/S1 interspace joint center and a hip joint center. The transpelvic link is a straight line between the right and left hip joint centers.

Axis System: A frontal plane (YZ) will be established using symphysis and the right and left anterior superior iliac spines. The XY-plane will be constructed as a perpendicular to the YZ plane passing through the right and left anterior superior iliac spines. The XZ-plane will be constructed as a normal to the XY and YZ-planes passing through symphysis. The point of origin will lie on a line passing through the right and left anterior superior iliac spines approximately at the midpoint of the bispinous diameter. The +X-axis will pass anteriorly along the intersection of the XY- and YZ-planes. The +Y-axis will pass laterally along the intersection of the XY- and YZ-planes and the +Z axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Upper Arm

Link: The straight line between the glenohumeral and elbow joint centers of rotation.

Axis System: A para-sagittal plane (XZ) will be constructed with the arm in the extended anatomical position using the glenohumeral and elbow joint centers of rotation and a point on the anterior surface of the skin overlying the maximum protrusion of the biceps brachii muscle approximately at the middle of the upper arm. The YZ-plane will be established perpendicular to the XZ-plane passing through the glenohumeral and elbow joint centers of rotation. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through the anterior surface point. Thus, the origin of the axis system will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Forearm

Link: The straight line between the elbow and wrist joint centers of rotation.

Axis System: A para-sagittal plane (XZ) will be established with the arm in the extended anatomical position using the elbow and wrist joint centers of rotation and a point on the anterior surface of the skin mid-way along the length of the forearm. The YZ-plane will be established as a perpendicular to the XZ-plane passing through the elbow and wrist joint centers. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through the anterior surface point. Thus, the origin will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Hand

Link: The straight line between the wrist joint center of rotation and the center of mass of the hand.

Axis System: Formed relative to a para-sagittal plane (XZ) with the arm and hand in the extended anatomical position using the wrist joint center of rotation, the most dorsal point on metacarpal III and the most distal point at the tip of phalanx III. The YZ-plane will be established as a perpendicular to the XZ-plane and will pass through the wrist joint center and the phalanx III distal point. The XY-plane will be formed as a normal to the XZ- and YZ-planes passing through the metacarpale III landmark. Thus, the point of origin of the axis system will lie at the intersection of the three orthogonal planes. The +X-axis will pass

anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Thigh

Link: The straight line between the hip and knee joint center of rotation.

Axis System: Formed relative to a para-sagittal plane (XZ) with the leg in the extended anatomical position using the hip and knee joint centers of rotation and a point on the anterior surface of the thigh lying approximately at mid-segment. The YZ-plane will be established as a perpendicular to the XZ-plane passing through the knee and hip joint centers of rotation. The XY-plane will be established as a normal to the YZ- and XZ-planes passing through the anterior surface point. Thus, the origin of the axis system will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y axis will pass laterally along the intersection of the XZ- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Shank

Link: The straight line between the knee and ankle joint centers of rotation.

Axis System: Formed relative to a para-sagittal plane (XZ) with the leg in the extended anatomical position using the knee and ankle joint centers and a point on the anterior surface approximately at mid-segment. The YZ-plane will be constructed as a perpendicular to the XZ-plane passing through the knee and ankle joint centers of rotation. The XY-plane will be formed as a normal to the XZ- and YZ-planes passing through the anterior surface landmark. Thus, the point of origin of the axis system will lie at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Foot

Link: The straight line between the ankle joint center of rotation and the center of mass of the foot.

Axis System: Formed relative to a para-sagittal plane (XZ) with leg in the extended anatomical position using the ankle joint center, the most posterior point on the heel, and most anterior point on the tip of the second toe. The YZ-plane is constructed perpendicular to the XZ-plane passing through the most posterior

and anterior points of the foot. The XY-plane is formed as a normal to the XZ- and YZ-planes passing through the ankle joint center. Thus, the point of origin of the axis system lies at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-axes; and the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

APPENDIX B
REGRESSION EQUATIONS

APPENDIX B

REGRESSION EQUATIONS

Tables 2, 3 and 4, regression equations for estimating center of mass, weight and volume of body segments, present a series of two- and three-step equations for predicting individual segment centers of mass, weight and volume from anthropometry. The regression equations are relatively simple to use but are given here in a form which differs somewhat to the customary form

The first entry in Table 2 is for predicting the location of the center of mass of the head and trunk as a distance from the top of the head (vertex). The equation is to be read as:

$$\text{CM of Head and trunk from vertex} = .859 \text{ Bicristal breadth} + 23.539 (\pm 1.20)$$

The two and three-step equations are correspondingly to be read as:

$$\begin{aligned} \text{CM of Head and trunk from vertex} = & .491 \text{ Bicristal breadth} + \\ & .408 \text{ Head-trunk length} + 1.313 (\pm 1.01) \end{aligned}$$

$$\begin{aligned} \text{CM of Head and trunk from vertex} = & .621 \text{ Bicristal breadth} + \\ & .582 \text{ Head-trunk length} - .181 \text{ Stature} + 14.050 (\pm 0.75) \end{aligned}$$

As the number of anthropometric variables in the equation increases, the correlation coefficient increases and the standard error of estimate decreases.

For the Head and trunk, the CM is located only as a distance from vertex (Z axis); for the majority of the other segments, the CM is located both in the Z axis and at a distance from the anterior surface of the segment (X axis). The location of the CM in the Y axis was assumed in this study to lie in the medial-lateral center of the segment.

TABLE 1
REGRESSION EQUATIONS FOR ESTIMATING LINK LENGTHS DIRECTLY FROM ANTHROPOMETRIC MEASURES
OF BONE LENGTHS FROM DEMPSTER, SHERR AND PRIEST (1964)

Empirical Equation	Standard Error of Estimate	Correlation Coefficient
Ulna Length = $23.7922 + (0.9810 \times \text{Radius Length})$	4.58	.94
Humerus Length = $64.4829 + (0.9683 \times \text{Radius Length})$	9.97	.81
Forearm-Link Length = $1.0709 \times \text{Radius Length}$	--	--
Arm-Link Length = $58.0752 + (0.9646 \times \text{Radius Length})$	8.92	.94
Radius Length = $7.9728 + (0.9002 \times \text{Ulna Length})$	4.39	.94
Humerus Length = $74.0856 + (0.9688 \times \text{Ulna Length})$	11.07	.76
Forearm-Link Length = $0.9870 \times \text{Ulna Length}$	--	--
Arm-Link Length = $66.2621 + (0.8665 \times \text{Ulna Length})$	9.90	.94
Femur Length = $125.6879 + (0.9067 \times \text{Tibia Length})$	18.39	.73
Fibula Length = $31.3653 + (0.9252 \times \text{Tibia Length})$	5.28	.97
Shank-Link Length = $1.0776 \times \text{Tibia Length}$	--	--
Thigh-Link Length = $132.8253 + (0.8172 \times \text{Tibia Length})$	16.57	.73
Femur Length = $101.8815 + (0.9629 \times \text{Fibula Length})$	11.45	.87
Tibia Length = $8.6266 + (1.0110 \times \text{Fibula Length})$	5.53	.97
Shank-Link Length = $8.2184 + (1.0904 \times \text{Fibula Length})$	5.95	.97
Thigh-Link Length = $92.0397 + (0.8699 \times \text{Fibula Length})$	10.34	.87

TABLE 2
REGRESSION EQUATIONS TO ESTIMATE CENTER OF MASS OF BODY SEGMENTS
FROM CLAUSER, ET AL. (1969)¹

Segment	CM Measured from	Independent Regression Variables			Constant	R	Se _{est}
		Bicristal breadth ²	Head-torso length	Stature			
Head & trunk	Top of head	.859			+ 23.539	.897	1.20
		.491	+ .402		+ 1.313	.935	1.01
		.621	+ .582	- .181	+ 14.050	.968	.75
Total leg	Trochanterion	Tibiale height	Calf circum- ference	Upper thigh circumference			
		.518			+ 11.016	.638	1.52
		.534	+ .099		+ 7.235	.650	1.57
Total leg	Anterior aspect	.562	+ .404	- .264	+ 9.061	.721	1.50
		AP at CM ³	Weight	Iliac crest skinfold			
		.530			+ 1.212	.695	.62
Total arm	Acromion	.795	- .053		+ 1.499	.817	.52
		.935	- .054	- .050	+ 0.408	.894	.43
		B humerus- rad. length ⁴	Forearm circumference	Arm circum- ference (axillary)			
Total arm	Acromion	.966			+ 2.336	.684	1.67
		.947	+ .391		- 7.353	.729	1.64
		.963	+ .918	- .571	- 4.909	.342	1.35
Head	Top of head	Head circumference	Height of head				
		.293			- 5.573	.704	.55
Head	Back of head	.246	+ .159		- 6.711	.731	.55
		Head circumference	Head breadth				
Head	Back of head	.158			- 1.039	.468	.55
		.238	- .570		+ 3.376	.541	.55
Trunk	Suprasternale	Bi-spinous breadth	Iliac crest skinfold	Trunk length			
		.578			+ 8.102	.846	.79
		.622	- .066		+ 7.741	.900	.68
Thigh	Trochanterion	.471	- .058	+ .166	+ 1.683	.926	.61
		Trochanterion height	Knee breadth (bone)	Iliac crest			
		.250			- 5.902	.841	.68
Thigh	Anterior aspect	.214	+ .902		- 11.660	.918	.52
		.227	+ .989	- .033	- 13.362	.934	.49
		AP at CM ⁴					
Shank & foot	Tibiale	.595			- .956	.838	.69
		Tibiale height	Calf circum- ference				
		.360			+ 5.226	.789	.68
Shank & foot	Anterior aspect	.335	- .159		+ 11.267	.871	.57
		AP at CM ⁴	Calf length				
		.539			- 1.731	.782	.40
Shank & foot	Anterior aspect	.646	+ .114		- 7.044	.850	.35

¹All dimensions are given in centimeters except skinfolds which are given in millimeters.

²For a precise definition of all dimensions, see Clauser, et al. (1969).

³Anterior-posterior

⁴Ball of humerus-radiale length.

TABLE 2 - Concluded

<u>Segment</u>	<u>CM Measured from</u>	<u>Independent Regression Variables</u>			<u>Constant</u>	<u>R</u>	<u>Se est</u>
Shank	Tibiale	Tibiale height	Knee breadth (bone)				
		.276			+ 1.709	.800	.50
		.309	- .558		+ 5.786	.872	.43
Shank	Anterior aspect	AP at CM ²	Calf length				
		.455			- 0.301	.665	.53
		.503	+ .101		- 4.688	.725	.51
Foot	Heel	Foot length	Ankle circumference	Lateral mal- leolus height			
		.217			+ 5.729	.566	.33
		.233	+ .135		+ 2.627	.712	.29
		.153	+ .137	+ .444	+ 1.403	.827	.25
Foot	Sole	Arch circumference					
		.325			- 4.639	.672	0.47
Upper arm	Acromion	B. humerus- ₃ rad. length	Arm Circumference (axillary)	Elbow Breadth (bone)			
		.707			- 4.563	.689	1.21
		.710	- .045		- 3.333	.691	1.26
		.329	- .250	+ 2.827	- 6.168	.918	.72
Upper arm	Anterior aspect	AP at CM ²					
		.444			+ .665	.874	.23
Forearm & hand	Radiale	Wrist breadth (bone)	Radiale-styilion length	Forearm Circumference			
		2.765			+ .405	.764	.72
		1.962	+ .379		- 4.822	.847	.62
		1.617	+ .585	- .331	+ .510	.929	.46
Forearm & hand	Anterior aspect	AP at CM ²	Elbow breadth (bone)	Styl.-meta ₄ III length			
		.890			- 2.355	.913	.25
		.900	- .280		- .385	.936	.23
		.890	- .313	- .229	- 2.153	.974	.16
Forearm	Radiale	Radiale-styilion length	Wrist breadth (bone)				
		.537				- 3.808	.788
		.440	+ .761			- 5.645	.821
Forearm	Anterior aspect	AP at CM ²					
		.790			- 2.295	.843	.35
Hand	Metacarpale III	Wrist breadth (bone)	Hand circumference				
		.358				- .415	.272
		.657	- .202			+ 2.130	.486
Hand	Medial aspect	Wrist breadth (bone)	Hand breadth				
		1.224				- 2.226	.769
		1.038	+ .248			- 3.271	.810

⁴ Stylion-Metacarpale III length.

TABLE 3
REGRESSION EQUATIONS FOR ESTIMATING SEGMENT WEIGHTS
FROM CLAUSER, MCCONVILLE AND YOUNG (1969)*

<u>Segment</u>	<u>Independent Regression Variables</u>			<u>Constant</u>	<u>R</u>	<u>Se est</u>
Head & trunk	Body Weight	Trunk length**	Chest depth	Constant		
	.580			+ .009	.968	1.36
	.521	+ .362		- 17.077	.980	1.11
	.491	+ .504	+ .370	- 31.122	.987	.93
Total leg	Body Weight	Calf circum- ference	Upper thigh circumference	- .000	.919	.62
	.115	+ .221		- 3.792	.954	.50
	.094	+ .146	+ .113	- 5.455	.964	.46
Total arm	Body Weight	Wrist circumference	Biceps circumference	+ .132	.883	.23
	.047			- 1.894	.929	.19
	.031	+ .186		- 3.041	.952	.16
Head						
	Head circumference	Weight				
	.148			- 3.716	.814	.20
Trunk				- 2.189	.875	.17
	Body Weight	Trunk length	Chest circumference	- 2.837	.966	1.33
	.551			- 19.186	.979	1.11
Thigh				- 35.460	.986	.92
	.494	+ .347				
	.349	+ .423	+ .229			
Shank & foot	Body Weight	Upper thigh circumference	Iliac crest skinfold	- 1.123	.893	.54
	.120			- 4.641	.933	.45
	.074	+ .138		- 4.216	.944	.43
Shank						
	.074	+ .123	+ .027			
Foot	Calf circumference	Tibiale height	Ankle circumference	- 1.279	.934	.16
	.165			- 3.824	.971	.11
	.172	+ .051		- 4.915	.982	.09
Upper arm						
	.130	+ .058	+ .103			
Forearm & hand	Calf circumference	Tibiale height	Ankle circumference	- 1.318	.933	.14
	.135			- 3.421	.971	.09
	.141	+ .042		- 4.208	.979	.08
Forearm						
	.111	+ .047	+ .074			
Hand	Body Weight	Ankle circumference	Foot length	+ .369	.810	.06
	.009			- .030	.882	.05
	.005	+ .033		- .869	.907	.04
Upper arm						
	.003	+ .048	+ .027			
Forearm & hand	Body Weight	Arm circumfer- ence (axillary)	Acromion- rad. length	- .238	.879	.14
	.030			- 1.280	.931	.12
	.019	+ .060		- 3.101	.961	.09
Forearm						
	.007	+ .092	+ .050			
Hand	Wrist circumference	Forearm circumference	Radiale-styloid length	- 1.295	.874	.10
	.168			- 1.987	.919	.09
	.132	+ .049		- 2.543	.940	.08
Forearm						
	.103	+ .046	+ .043			
Hand	Wrist circumference	Forearm circumference		- .913	.827	.09
	.119			- 1.650	.920	.06
	.081	+ .052				
Hand						
	Wrist circumference	Wrist breadth (bone)	Hand breadth	- .418	.863	.03
	.051			- .660	.917	.03
	.038	+ .080		- .746	.942	.02
	.029	+ .075	+ .031			

*Weight is given in kilograms, skinfolds in millimeters and all other dimensions in centimeters.

**For a precise definition of all dimensions, see Clauser, et al. (1969).

TABLE 4
REGRESSION EQUATIONS TO ESTIMATE SEGMENT VOLUME
FROM CLAUSER, ET AL. (1969)*

Segment	Independent Regression Variables			Constant	R	S _{est}
	Body Weight	Chest circumference**	Trunk length			
Head & trunk	.563			+ .187	.951	1.65
	.358	+ .353		- 19.331	.970	1.35
	.228	+ .450	+ .448	- 45.797	.988	.90
Total leg	Body Weight	Upper thigh circumference				
	.157			- .345	.924	.58
	.105	+ .157		- 4.370	.955	.47
Total arm	Body Weight	Wrist circumference	Biceps circumference			
	.047			- .106	.907	.20
	.032	+ .165		- 1.850	.945	.16
Head				- 2.913	.968	.13
Trunk	Head circumference	Weight				
	.173			- 5.453	.883	.17
	.139	+ .012		- 4.301	.912	.16
Thigh	Body Weight	Waist breadth	Chest circumference			
	.534			- 2.343	.949	1.59
	.389	+ .476		- 7.392	.968	1.33
Shank & foot				- 26.817	.988	.86
Shank	Body Weight	Upper thigh circumference	Iliac crest skinfold			
	.116			- 1.149	.888	.54
	.073	+ .128		- 4.390	.924	.47
Shank & foot				- 3.760	.950	.40
Shank	Shank circumference	Tibiale height	Ankle circumference			
	.148			- 1.056	.911	.17
	.155	+ .050		- 3.555	.955	.13
Foot				- 4.910	.975	.10
Foot	Shank circumference	Tibiale height	Ankle circumference			
	.123			- 1.170	.908	.15
	.130	+ .044		- 3.396	.956	.11
Upper arm				- 4.427	.973	.09
Forearm & hand	Body Weight	Ankle circumference	Foot length			
	.008			+ .360	.810	.05
	.005	+ .029		- .025	.875	.04
Forearm				- .794	.901	.04
Forearm	Body Weight	Arm circumference (axillary)	Acromion-rad. length			
	.030			- .330	.886	.14
	.018	+ .070		- 1.600	.953	.10
Hand				- 3.234	.976	.07
Forearm & hand	Wrist circumference	Forearm circumference	Radiale-styilion length			
	.153			- 1.181	.890	.09
	.117	+ .048		- 1.847	.943	.07
Forearm				- 2.278	.960	.06
Forearm	Wrist circumference	Forearm circumference				
	.111			- .875	.842	.08
	.072	+ .053		- 1.622	.954	.05
Hand	Wrist circumference	Wrist breadth (bone)	Hand breadth			
	.048			- .410	.885	.03
	.036	+ .071		- .617	.935	.02
Hand				- .686	.958	.02

*Weight is given in kilograms, skinfolds in millimeters and all other dimensions in centimeters.

**For a precise definition of all dimensions, see Clauser, et al. (1969).

TABLE 5
REGRESSION EQUATIONS FOR PREDICTING PRINCIPAL MOMENTS OF INERTIA (I_{xx} , I_{yy} , I_{zz}) FROM CHANDLER ET AL. (1975)

	R	Se _{est}		R	Se _{est}
Head			Hand (Right and Left)		
I_{xx} = 2.129 Body Wgt. + 32030	.72	33217	I_{xx} = .106 Body Wgt. + 294	.77	1279
I_{yy} = 1.676 Body Wgt. + 54818	.64	32598	I_{yy} = .117 Body Wgt. - 1760	.86	1206
I_{zz} = 3.186 Body Wgt. + 6846	.75	45033	I_{zz} = .056 Body Wgt. - 1703	.72	793
I_{xx} = 61.333 Seg. Wgt. - 73825	.75	28310	I_{xx} = 21.162 Seg. Wgt. - 977	.92	795
I_{yy} = 50.190 Seg. Wgt. - 36367	.70	27066	I_{yy} = 21.495 Seg. Wgt. - 2453	.94	668
I_{zz} = 108.133 Seg. Wgt. - 234457	.94	20880	I_{zz} = 11.414 Seg. Wgt. - 2443	.87	563
I_{xx} = 71.289 Seg. Vol. - 99078	.72	33413	I_{xx} = 22.560 Seg. Vol. - 880	.92	798
I_{yy} = 67.587 Seg. Vol. - 91812	.77	27265	I_{yy} = 23.091 Seg. Vol. - 2417	.95	632
I_{zz} = 133.055 Seg. Vol. - 302860	.93	24479	I_{zz} = 12.216 Seg. Vol. - 2408	.87	558
Torso			Thigh (Right and Left)		
I_{xx} = 296.900 Body Wgt. - 3156034	.96	1379345	I_{xx} = 22.206 Body Wgt. - 302878	.93	131640
I_{yy} = 284.493 Body Wgt. - 7664879	.94	1698612	I_{yy} = 22.410 Body Wgt. - 270933	.88	176759
I_{zz} = 102.507 Body Wgt. - 2895524	.98	335637	I_{zz} = 7.333 Body Wgt. - 259219	.86	63057
I_{xx} = 559.413 Seg. Wgt. - 2823363	.98	1065961	I_{xx} = 174.770 Seg. Wgt. - 17732	.96	103026
I_{yy} = 538.593 Seg. Wgt. - 7432970	.96	1404515	I_{yy} = 178.913 Seg. Wgt. - 70	.92	145457
I_{zz} = 189.523 Seg. Wgt. - 2657654	.98	353958	I_{zz} = 58.390 Seg. Wgt. - 169540	.90	54426
I_{xx} = 621.812 Seg. Vol. - 8456005	.99	733465	I_{xx} = 177.458 Seg. Vol. - 14973	.95	104278
I_{yy} = 601.400 Seg. Vol. - 12964208	.97	1100518	I_{yy} = 181.809 Seg. Vol. + 1809	.92	145763
I_{zz} = 205.205 Seg. Vol. - 4349563	.96	448759	I_{zz} = 59.315 Seg. Vol. - 168797	.90	54587
Upper Arm (Right and Left)			Shank (Right and Left)		
I_{xx} = 1.315 Body Wgt. + 56859	.65	21982	I_{xx} = 5.934 Body Wgt. + 6359	.83	58521
I_{yy} = 1.006 Body Wgt. + 69616	.67	16355	I_{yy} = 5.345 Body Wgt. + 49951	.84	49951
I_{zz} = .484 Body Wgt. - 9094	.91	3139	I_{zz} = .955 Body Wgt. - 33393	.86	8078
I_{xx} = 76.750 Seg. Wgt. - 577	.76	18907	I_{xx} = 133.207 Seg. Wgt. + 36264	.80	62315
I_{yy} = 51.383 Seg. Wgt. + 39365	.68	16149	I_{yy} = 125.929 Seg. Wgt. + 53889	.85	47940
I_{zz} = 26.025 Seg. Wgt. - 26122	.98	1644	I_{zz} = 22.252 Seg. Wgt. - 30775	.87	7950
I_{xx} = 74.043 Seg. Vol. + 4887	.77	18635	I_{xx} = 145.497 Seg. Vol. + 27035	.82	59030
I_{yy} = 49.456 Seg. Vol. + 43236	.68	18039	I_{yy} = 134.580 Seg. Vol. + 47599	.87	45097
I_{zz} = 24.846 Seg. Vol. - 23785	.98	1644	I_{zz} = 23.493 Seg. Vol. - 30273	.86	8092
Forearm (Right and Left)			Foot (Right and Left)		
I_{xx} = 1.084 Body Wgt. - 4812	.84	9973	I_{xx} = .432 Body Wgt. + 4481	.65	7229
I_{yy} = 1.062 Body Wgt. - 5444	.87	8652	I_{yy} = .359 Body Wgt. + 7328	.72	5081
I_{zz} = .271 Body Wgt. - 9020	.96	1090	I_{zz} = .141 Body Wgt. - 1915	.80	1542
I_{xx} = 63.300 Seg. Wgt. - 3888	.87	9219	I_{xx} = 60.816 Seg. Wgt. - 18255	.94	3202
I_{yy} = 60.290 Seg. Wgt. - 2628	.87	8647	I_{yy} = 47.772 Seg. Wgt. - 9206	.97	1693
I_{zz} = 15.760 Seg. Wgt. - 8683	.99	691	I_{zz} = 15.930 Seg. Wgt. - 6051	.92	990
I_{xx} = 63.515 Seg. Vol. - 565	.86	9484	I_{xx} = 49.804 Seg. Vol. - 7647	.75	6288
I_{yy} = 60.844 Seg. Vol. + 172	.87	8750	I_{yy} = 37.130 Seg. Vol. + 736	.74	4910
I_{zz} = 16.038 Seg. Vol. - 8091	.99	575	I_{zz} = 15.035 Seg. Vol. - 4864	.85	1356

APPENDIX C

CONVERSION TABLE OF MOMENTS OF INERTIA

APPENDIX C

TABLE 1

CONVERSION TABLE OF MOMENTS OF INERTIA

	lb-in^2	lb-ft^2	oz-in^2	cm^2	kg-cm^2	kg-m^2	oz-in-sec^2	lb-in-sec^2	lb-ft-sec^2	kg-m-sec^2	cm-m-sec^2
lb-in^2	---	6.947 (10^{-3})	1.600 (10^1)	2.929 (10^3)	2.929 (10^1)	2.929 (10^{-4})	4.145 (10^{-3})	2.591 (10^{-3})	2.159 (10^{-4})	2.993 (10^{-5})	2.993 (10^{-1})
lb-ft^2	1.440 (10^2)	---	2.304 (10^3)	4.217 (10^5)	4.217 (10^2)	4.217 (10^{-2})	5.967 (10^1)	3.729 (10^{-1})	3.108 (10^{-2})	4.308 (10^{-3})	4.308 (10^2)
oz-in^2	6.248 (10^{-2})	4.341 (10^{-4})	---	1.830 (10^2)	1.830 (10^{-1})	1.830 (10^{-5})	2.590 (10^{-3})	1.619 (10^{-4})	1.349 (10^{-5})	1.870 (10^{-6})	1.870 (10^{-1})
cm^2	3.414 (10^{-4})	2.371 (10^{-6})	5.463 (10^{-3})	---	10^{-3}	10^{-7}	1.415 (10^{-5})	8.844 (10^{-7})	7.370 (10^{-8})	1.022 (10^{-8})	1.022 (10^{-3})
kg-cm^2	3.414 (10^{-1})	2.371 (10^{-3})	5.463 (10^1)	10^3	---	10^{-4}	1.415 (10^{-2})	8.844 (10^{-4})	7.370 (10^{-5})	1.022 (10^{-5})	1.022 (10^1)
kg-m^2	3.413 (10)	2.371 (10^1)	5.463 (10^4)	10^7	10^4	---	1.415 (10^2)	8.844 (10^1)	7.370 (10^{-1})	1.022 (10^{-1})	1.022 (10^4)
oz-in-sec^2	2.413 (10^1)	1.676 (10^{-1})	3.861 (10^2)	7.067 (10^4)	7.067 (10^1)	7.067 (10^{-3})	---	6.250 (10^{-2})	5.208 (10^{-3})	7.220 (10^{-4})	7.220 (10^4)
lb-in-sec^2	3.860 (10^2)	2.681 (10^1)	6.178 (10^3)	1.131 (10^6)	1.131 (10^3)	1.131 (10^{-1})	1.600 (10^1)	---	8.333 (10^{-2})	1.155 (10^{-2})	1.155 (10^3)
lb-ft-sec^2	4.632 (10^3)	3.218 (10^1)	7.413 (10^4)	1.357 (10^7)	1.357 (10^4)	1.357 (10^1)	1.920 (10^2)	1.200 (10^1)	---	1.386 (10^{-1})	1.386 (10^4)
kg-m-sec^2	3.341 (10^4)	2.321 (10^2)	5.347 (10^5)	9.788 (10^7)	9.788 (10^4)	9.788 (10^1)	1.385 (10^3)	8.656 (10^1)	7.214 (10^1)	10^3	10^5
cm-m-sec^2	3.341 (10^1)	2.321 (10^{-1})	5.347 (10^2)	9.788 (10^4)	9.788 (10^1)	9.788 (10^{-3})	1.385 (10^1)	8.656 (10^{-2})	7.214 (10^{-3})	---	10^{-5}
	3.341 (10^{-1})	2.321 (10^{-3})	5.347 (10^1)	9.788 (10^2)	9.788 (10^{-1})	9.788 (10^{-5})	1.385 (10^{-2})	8.656 (10^{-4})	7.214 (10^{-5})	10^{-5}	---