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TRANSITION

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The National Academy of Sciences began publication of *Artificial Limbs* in 1954 because, at that time, there was available no periodical for the systematic dissemination of the results of research in limb prosthetics. Since that time 33 issues have been published and made available without charge to an average of 5,000 individuals concerned with the management of amputees.

Also, since the initiation of *Artificial Limbs,* the Veterans Administration Prosthetic and Sensory Aids Service has introduced the *Bulletin of Prosthetic Research,* and the American Orthotic and Prosthetic Association and the American Academy of Orthotists and Prosthetists publish the journal *Orthotics and Prosthetics* which is now devoted entirely to technical and professional topics.

Thus, in keeping with the philosophy that the National Academy of Sciences should not undertake programs that can be carried out by others, publication of *Artificial Limbs* will be discontinued with this issue. This decision will permit the Committee on Prosthetics Research and Development and the Committee on Prosthetic-Orthotic Education to devote the time and funds that would have gone into production of *Artificial Limbs* to the production of monographs and other publications that are not apt to be made available otherwise.

Information that would have appeared in *Artificial Limbs* will now be found in the *Bulletin of Prosthetics Research* and *Orthotics and Prosthetics.*

The reception given to *Artificial Limbs* through the years has been very rewarding to the staff, and even though it is with regret that we must advise discontinuance of its publication, we feel that the move is in the best interest of the Prosthetics and Orthotics Program.

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Body Segment Parameters, Part II[1]

RENATO CONTINI[2]

The performance of human (animal) activity requires the expenditure of energy. During the contraction of the muscles involved in this activity, chemical energy is converted first into mechanical energy, then into work and heat. Some of this chemical energy is required for maintenance of body functions. In movement, however, much of the mechanical energy is required to overcome friction and tissue displacement at the joints, gravity, inertial forces, air and water resistance—all of which oppose the action desired.

Biomechanics is the science that is concerned with such effects. In order to understand better the biomechanics of movement, it is necessary to know certain characteristics of the segments involved. Among these characteristics are the mass of the segments, their centers of mass, and their mass moments of inertia. The characteristics (body parameters) themselves are not readily obtained on living subjects.

It was the purpose of two studies conducted at the New York University School of Engineering and Science to obtain some of these body parameters. The first of these studies *(6)*, completed in 1966, was conducted on normal, healthy American males in the age range of 20-40 years. The second study (3), completed in 1970, was conducted on a random selection of adults, young males and females 20-30 years of age, some females in the 40-50 age bracket, and a number of amputees and hemiplegics, male and female, in all age ranges.

A history, survey of measurement techniques, and data developed over the years was given in "Body Segment Parameters: A Survey of Measurement Techniques," which appeared in *Artificial Limbs*, Spring 1964 (7). Also, a condensation of four of the most important monographs in this field ("Center of Gravity of the Human Body" by W. Braune and O. Fischer; "Theoretical Fundamentals for a Mechanics of Living Bodies" by O. Fischer; "The Human Motor" by J. Amar; and "Space Requirements of the Seated Operator" by W. T. Dempster) has been prepared by Krogman and Johnston *(10)* under the sponsorship of the United States Air Force.

METHODS

Most studies undertaken previously used cadavers, but in a few studies, including those at New York University, living subjects were used. Although some available measuring techniques for compiling the data are similar for live subjects and for cadavers, other techniques must obviously differ. In general, the techniques covered here are for living subjects; thus, all techniques used on dissected cadavers are not included. When living subjects are used, particularly the elderly and those suffering with some affliction or disability, any technique utilized must be at the convenience of the subject. Some subjects cannot comfortably assume the necessary postures during the measurement processes, while for some others the procedures are physically impossible. As a result, not all measurements can be taken on all subjects, but, because of the various tech-

[1] The investigations on which this article is based were supported principally by two research special projects grants—one from the Office of Vocational Rehabilitation and the other from the Social and Rehabilitation Service, Dept. of Health, Education, and Welfare.

[2] Prosthetic-Orthotic Education Program, UCLA, Los Angeles, Calif.

niques available, most of the desired data can be obtained.

The techniques are only briefly presented here because more adequate descriptions are available in other references.

VOLUME DETERMINATION

The body and all of its segments are irregular solids. The volume of an irregular solid may be obtained or approximated in a number of ways: by mensuration, immersion, or photogrammetry. Only the first two were used in both studies.

Mensuration

A relatively good approximation of body-segment volume can be obtained by using circumferential measurements at certain selected stations on the segment and the linear dimensions between any two consecutive circumferential measurements. If all these measurements are known for the full length of the segment, then an approximate volume can be determined. Accuracy will increase with the increased number of such measurements. This technique assumes that any two successive cross sections of the member are parallel and essentially similar geometrically. In that event, the volume contained within the two cross sections may be expressed as:

$$V = \frac{h}{3}[B_1 + B_2 + (B_1B_2)^{1/2}] \quad \text{where,} \quad [1]$$

B_1 and B_2 are the areas of the respective cross sections and h is the linear distance between them.

It is obviously impossible to obtain cross-sectional areas on the body segments of living subjects. If it is assumed, however, that the cross sections of the limbs are elliptical, it is possible to establish a relationship between the cross-sectional area and the perimeter at any chosen level. For any segmental portion between two levels, the volume may now be expressed as:

$$V_s = \frac{K}{2}(P_1 + P_2)^2h, \quad \text{where,} \quad [2]$$

P_1 and P_2 are the circumferential dimensions at levels 1 and 2
h is the distance between P_1 and P_2
K is a constant for which the most reasonable value appears to be 0.0778

For a total limb divided into n segments, each *h* distance apart:

$$V_S = K(P_1 + P_2 + P_3, \ldots, P_n)^2 \cdot h(n - 1) \quad [3]$$

The derivation of this equation is given in reference *3*.

Immersion

In this method, the segment whose volume is to be determined is immersed in water. Incremental volumes are taken of the segment whose total volume then is the sum of these increments. For these studies, four tanks were specially designed: an arm tank, a hand tank, a leg tank, and a foot tank. Each tank was constructed of Plexiglas, the first three cylindrical in cross section, and the last, rectangular.

The limb or body segment was completely immersed in the tank. Water was permitted to drain off in controlled increments, each representing a known change in cylinder height. Drained water was collected and measured. The difference in volume between that collected and that obtainable without the body segment in place (the actual volume of the tank for that increment) represents the volume of the body segment contained within the height increment. Whenever possible, these increments were 2.0 cm apart, but, if subjects with limited physical tolerance had minimal cross-sectional variation, the increments were increased to every 4.0 cm apart.

Photogrammetry

Two types of photogrammetric techniques are available—mono and stereo. In the former, lines or colored shadows are projected on the subject in such fashion as to produce a contour map on the particular segment of interest. The areas contained within these contours may be measured with a planimeter, and the same general equation for determining the volume as given previously may be used. Again, the sum of all the incremental volumes of the segment represents its total volume.

In stereophotogrammetry, two cameras are used side by side to create an illusion of depth when the two photographs are juxtaposed. The resulting picture is treated as an aerial photograph of terrain upon which contour levels are applied. These then are treated as in monophotogrammetry.

DENSITY DETERMINATION

To obtain the overall body density of living subjects is extremely difficult. To obtain the density of individual segments on living subjects is virtually impossible. There are ways, however, to obtain fairly accurate values. The problems involved will not be discussed here; some of them are described in the two referenced reports *(3, 6).*

Empirical (Whole Body)

Whole-body volume may be approximated in several ways. The mass may be obtained by weighing accurately. The density is the ratio of mass to volume. For lean bodies, the density is higher than for fat bodies. One provisional formula for determining density, developed by Dupertuis in 1950 *(8),* makes use of Sheldon's somatotyping system *(12)* and introduces the first component (x) of the system into the equation:

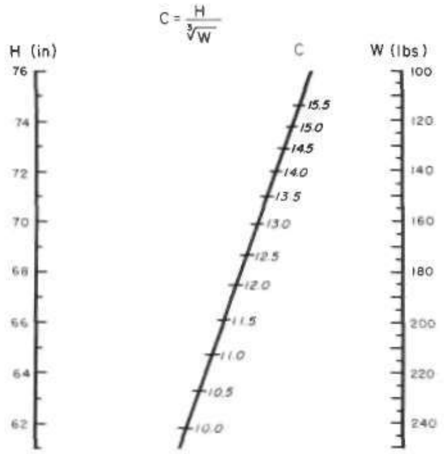
$$d(ensity) = 1.094 - 0.0119x$$

A second equation developed by the Biomechanics Group at NYU, using data developed by Behnke *(1),* is based on the height *(H)* in inches, and weight *(W)* in pounds of the individual (figs. 1 and 2):

$$d = 0.6905 + 0.0297C \quad \text{where,} \quad C = HW^{-1/3} \text{ (see Figs. 1 \& 2)} \qquad [4]$$

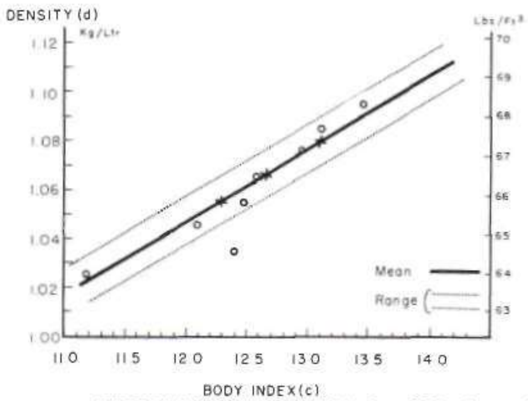
Anthropometric (Whole Body)

Many studies have established the reasonably close relationship between body fat and certain skin-fold thicknesses (2). The equations used for the NYU study were those developed by Pascale *(11).*



NOMOGRAM FOR BODY INDEX (c) DETERMINATION

Fig. 1.



DETERMINATION OF THE WHOLE BODY DENSITY

Fig. 2.

The first depends on the measurement of the skin-fold thickness at the triceps:

$$d(ensity) = 1.0923 - 0.0202(St) \times 0.1$$

The second depends on the measurement of the skin-fold thickness at the scapula:

$$d = 1.0896 - 0.0179(Ss) \times .1$$

Mensuration (Whole Body)

Skerlj in 1954 *(13)* developed a method for determining whole-body volume. He measured 10 circumferential dimensions and 6 linear dimensions (fig. 3). From these he developed a formula that gives an approximate value for whole-body volume.

The NYU group presented *(3)* a modified equation using the Skerlj notation and included some correction factors derived by applying the equation to five subjects for whom the volume of the various body segments was known. The modified formula is:

$$V = 0.0778\left[\left(\frac{P_1 + P_2}{2}\right)^2 h_1 + 0.890\left(\frac{P_3 + P_4 + P_5}{3}\right)^2 h_2 + 1.40(P_6{}^2h_3 + P_7{}^2h_4) + 2.02\left\{\left(\frac{P_8 + P_9}{2}\right)^2 h_5 + P_{10}^2 h_6\right\}\right] \quad [5]$$

Where $P_1, P_2, P_3, \ldots, P_n$ are the circumferential diameters
n is the number of such dimensions
h is the distance between P_1 and P_n
k is a constant (0.0778)

With the volume so determined, the mass may be obtained by direct weighing and the overall (whole body) density may be obtained:

$$d(ensity) = M(ass)/V(olume)$$

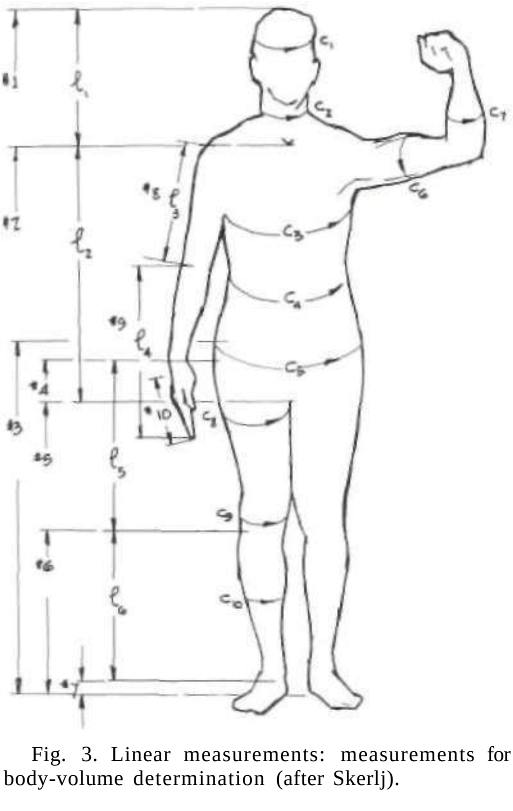


Fig. 3. Linear measurements: measurements for body-volume determination (after Skerlj).

Empirical (Body Segments)

Until recently, very little work has been done to establish segment densities. Harless (9) conducted some studies with cadavers, as did Dempster *(4, 5).* At NYU, in the first of the two studies, the mass of certain body segments was established by the reaction-board method, which is described below.

Based on these studies, two graphs were developed that relate whole-body density to body-segment density (figs. 4 and 5). These are approximations only, since no exact data are available.

MASS DETERMINATION

In studies conducted with cadavers, weight and eventually mass are obtained directly by accurate weighing techniques applied to the total segment or to its increments. In studies with live subjects, this cannot be done. The reaction-board method may be used.

Reaction-Board Method

This method is dependent on the validity of two assumptions. The first is that the center of mass can be established if the

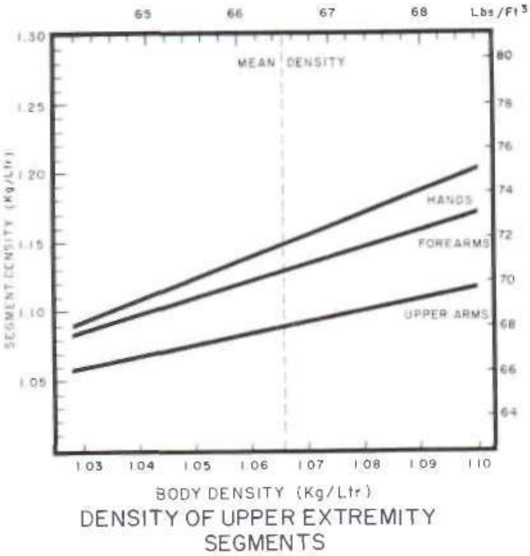


Fig. 4.

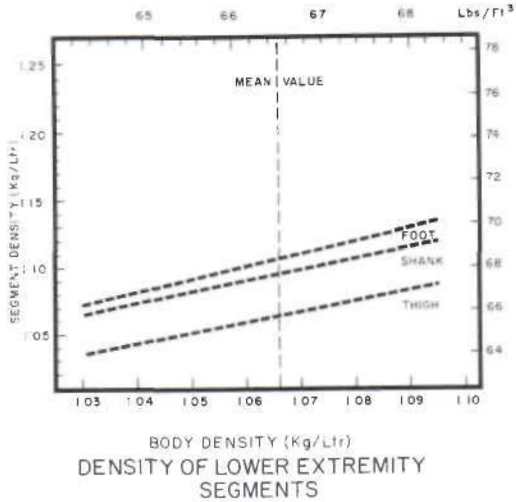


Fig. 5.

center of volume is known. This is true only if the density of the segment is constant along its entire length. The studies conducted by the Aerospace Medical Research Laboratory showed that the density is not constant along the segment and the variation in density is not the same for all segments.

The second assumption is that the rotation of a segment occurs about a single axis. If this were so, in the movement of a segment the centers of mass of all other body segments would remain fixed relative to the center of rotation. Since no body joint is uniaxial, and since the muscle masses shift in the course of any movement, this also is not quite correct.

Nonetheless, the method has been used (fig. 6). For the purpose, a board or platform is supported on two knife edges—one on a fixed base, the other on the platform of a weighing scale. The subject is. placed on the board in a position that can be maintained or reproduced if necessary. A reading is taken on the scale. The subject is then asked to flex the segment of interest (forearm, arm, etc.) through a given angle—usually 45 deg., 90 deg., or 135 deg. A new reading is taken. The mass of the segment can then be determined substituting the appropriate readings in the formula:

$$M = \frac{(S_m = S_o)\,D}{d(1 - \cos\varphi)} \quad \text{where:} \qquad [6]$$

S_m is the measured reaction force for a given position
S_0 is the measured reaction force for the basic position
D is the distance between board supports (knife edges)
d is the distance from the segment mass center to the proximal joint
φ is the angle between the segment and the horizontal

Empirical

For body segments the mass may be determined if the volume and density have been established. The mass, of course, is the product of the volume of the segment and the density of the segment.

$$Ms = Vsds$$

CENTER-OF-MASS DETERMINATION

The center of mass of the whole body may be determined readily by several methods since the mass is readily obtainable. The center of mass of a body segment on a live individual is not easily obtained, but may be approximated by one of several techniques.

Volumetric Approximation

A number of researchers, the NYU group included, have assumed that the density along the segment is constant and thus have concluded that the center of mass is coincident with the center of volume. Under this assumption, the center of volume, hence the center of mass, is found in the following way:

A base line is established, usually the proximal joint of the segment. This segment is divided into a number of increments for which the volume is obtained by one of several methods (*V1, V2, V3,..., Vn*). The distance to the center of volume is measured from the base line (*d1, d2, d3, . . ., dn*).

The center of volume is determined by dividing the sum of the products of each volume times its distance from the base line, by the sum of the volumes.

$$C_v = \frac{V_1 d_1 + V_2 d_2 + V_3 d_3 \ldots\ldots V_n\, d_n}{V_1 + V_2 + V_3 \ldots\ldots V_n} \quad [7]$$

$$C_v = \sum V_i\, d_i / \sum V_i = C_m \quad [8]$$

Reaction-Board Method

With cadavers, segments, or with plaster models of body segments, the center of mass may be obtained by use of the reaction board, previously described.

Of these techniques, the one using the cadaver segment and the reaction board is the most accurate; the true center will vary in this technique only by the change that has occurred in the body tissues after death. Use of the plaster-of-paris cast creates the same error as that obtained by use of the volumetric technique; i.e., the error is introduced because it is assumed that the density along the segment is constant, whereas the density in any segment usually increases from the proximal to the distal end. This occurs because the ratio of bone to muscle and fat increases distally.

SEGMENT MASS MOMENT OF INERTIA

The motions of body segments are essentially rotatory, and linear movement is the result of a number of coordinated rotatory motions. The motion is assumed to

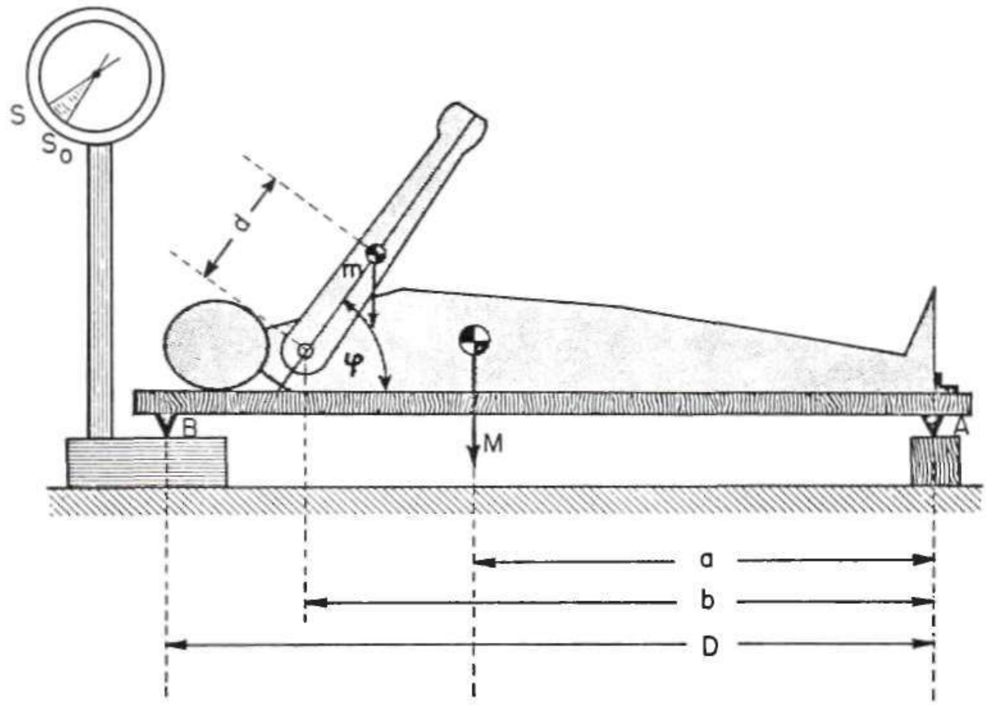


Fig. 6. Determination of the arm mass (reaction-board method).

occur about a fixed axis that is perpendicular to the plane in which the motion occurs. It is assumed that frictional and inertial forces occur in the plane of rotation. Rotation can be caused by a force at some distance from the axis of rotation, or by a force couple. In rotation, an inertial force resists angular acceleration which acts at the center of mass resulting in an inertial moment. This mass moment of inertia depends on the size, shape, and mass distribution of the body.

The mass moment of inertia may be determined in several ways.

Empirical

The mass moment of inertia of a body with respect to a given axis of rotation is the sum of the products of the mass increments *mi* (into which the total mass may be divided) by the square of their respective distances from the particular axis of rotation:

$$I = m_1 d_1^2 + m_2 d_2^2 + m_3 d_3^2 \ldots\ldots + m_n d_n^2 = \sum m_i d_i^2 \qquad [9]$$

Quick Release

If a force *(F)* is applied to a segment at some distance *(d)* from the axis of rotation of the segment, it will be imparted at an angular acceleration (a) in accordance with the equation:

$$Fd = Ia$$

Because of this relationship, it is possible to determine the mass moment of inertia (*I*) experimentally by this quick-release method.

In this method, the body segment of interest is arranged so that it may be free to swing about the proximal joint, which in turn is restrained from motion. At some distance (*d*) from the axis of rotation, a cable is attached to the segment such that it will prevent rotation in one direction. The other end of the cable is attached to a spring restraint, which in turn is attached to a force-measuring device. The subject is instructed to pull against the spring with a force *(F),* which is recorded. The cable is cut suddenly and the segment accelerates with an acceleration *(a)* that is appropriately recorded. By substitution of the known values *F, d, a,* the mass moment of inertia *(I)* can be obtained.

$$I = Fd/a$$

Pendulum

The period of a pendulum is related to the mass moment of inertia of the pendulum. For a simple pendulum, i.e., one where the mass is concentrated at some distance from the center of oscillation, the relationship is expressed by the equation:

$$I = WLT^2/4\pi^2 \quad \text{where,} \qquad [10]$$

W = mg = weight of the pendulum in pounds
L = distance from axis of rotation to mass center in feet
T = period of one oscillation in seconds
π = 3.1416

This method utilizes plaster casts of body segments or the severed cadaver segments. The segment or its counterpart is suspended at one point near the end of the segment. It is permitted to swing through an arc of limited magnitude. The period of oscillation is obtained by some appropriate instrumentation. The values that are obtained are substituted in the above equation.

RESULTS

Results are given for tests conducted both in the first and second series of experiments. In the first series of tests, data were collected on 12 male subjects in the age range of 20-40 years. In the second series of tests, data were collected on 9 male subjects in the age range of 20-30 years, 5 female subjects ages 17-20 years, and 3 female subjects ages 40-50 years, all without disabilities. Data were also recorded on 19 additional subjects with either hemiplegia or an amputation. In the second series of tests, not all data were recorded for every subject. The following tables contain the most valid data acquired.

VOLUMES

Table 1 contains the volume of body segments recorded during the first series of tests. There is only one major difference between the two series on males. In the first series, the value for volume of the upper arm—and hence the value for the whole arm—included the shoulder cap, i.e., the volume from the axilla to the acromion process. In the second series (table 2), the values of volumes for the upper and whole arm are only up to the axilla. On the basis of the mean values for the upper arm in the two series, the volume of the shoulder cap is approximately 36% of the whole upper arm.

In the second series of tests, a limited number of shoulder caps were cut off from the plaster-of-paris arms at the level of the axilla. Their dimensions, circumference at the axilla (c), and height to the acromion process *(h)* were taken. The volumes were obtained by immersion.

An approximate equation for determining the volume of the shoulder cap was then established:

$$\textit{Volume (shoulder cap)} = 0.0526\ hcc$$

This equation is approximate to ± 20% of the true value.

In all other respects, the two series of tests give comparable results. The differ-

TABLE 1. VOLUME OF BODY SEGMENTS IN LITERS (MALE, SERIES I)

Segment	Range	Mean	S. D.	C. V. in Percent
Hand	0.328– 0.428	0.384	0.035	9.1
Forearm	1.055– 1.296	1.175	0.084	7.2
Upper arm[a]	2.094– 3.047	2.412	0.334	13.9
Whole arm[a]	3.512– 4.583	3.971	0.376	9.5
Foot	0.670– 1.105	0.895	0.175	19.6
Shank	2.263– 3.272	2.818	0.399	14.2
Thigh	4.750– 8.456	6.378	1.464	22.9
Whole leg	8.338–12.788	10.091	1.758	17.4

[a] The volume of the upper arm and whole arm includes the shoulder cap.

TABLE 2. VOLUMES OF BODY SEGMENTS IN LITERS (MALES, SERIES II)

Segment	Range	Mean	S. D.	C. V. in Percent
Hand, right	0.306– 0.417	0.360	0.0413	11.5
Hand, left	0.317– 0.410	0.360	0.0102	2.8
Forearm, r	0.930– 1.535	1.212	0.174	14.4
Forearm, l	0.977– 1.492	1.223	0.175	14.3
Upper arm, r[a]	1.187– 1.876	1.555	0.218	14.0
Upper arm, l[a]	1.117– 1.965	1.556	0.277	17.8
Whole arm, r[a]	2.587– 3.628	3.133	0.336	10.7
Whole arm, l[a]	2.470– 3.582	3.096	0.357	11.5
Foot, r	0.80 – 1.08	0.892	0.117	13.1
Foot, l	0.80 – 1.08	0.904	0.099	11.0
Shank, r	2.14 – 3.86	3.162	0.459	14.5
Shank, l	2.41 – 3.58	3.092	0.398	12.9
Thigh, r	5.37 – 8.58	6.442	0.894	13.9
Thigh, l	5.27 – 8.51	6.453	0.911	14.1
Whole leg, r	8.84 –12.85	10.806	1.155	10.7
Whole leg, l	8.63 –12.91	10.645	1.332	12.5

[a] The values for the upper arm and whole arm do not include the shoulder cap.

ences in mean values are of the order of 1%-10%. Considering the limited numbers of subjects, 12 and 8 in the respective samples, the differences are not serious, and the mean values are useful in general computations. Of interest in the second series of tests is the close relationship between mean values for right-hand and left-hand volumes. The variation between means in most instances is less than the variation between the volume of right and left segments in any subject.

Table 3 indicates similar values for female subjects. There was greater inter-subject variation in this population than in that for the males. In view of this, and because there was such a limited number of subjects both in the younger and older age groups, the values for the two groups were combined. Even so, these mean values may be less accurate than those for the male population. They are presented, however, because few other similar data are available.

The body-segment volume may be expressed as a ratio or percentage of the whole-body volume. If it is desired to estimate body-segment volume, it is better to do so on the basis of the segment volume as a percentage of whole-body volume. This probably will give a more accurate result than using an average value for the volume of body segment.

Table 4 gives such values for the first

TABLE 3. VOLUMES OF BODY SEGMENTS IN LITERS (FEMALES)

Segment	Range	Mean	S. D.	C. V. in Percent
Hand, right	0.165- 0.357	0.281	0.063	22.4
Hand, left	0.174- 0.374	0.288	0.066	23.0
Forearm, r	0.546- 1.078	0.864	0.159	18.4
Forearm, l	0.601- 1.168	0.848	0.159	18.8
Upper arm, r	0.786- 1.416	1.135	0.226	19.9
Upper arm, l	0.764- 1.333	1.139	0.232	20.4
Whole arm, r	1.519- 2.828	2.281	0.395	17.3
Whole arm, l	1.650- 2.875	2.276	0.377	16.6
Foot, r	0.50 - 1.00	0.749	0.134	17.9
Foot, l[a]	0.52 - 0.79	0.670		
Shank, r	2.14 - 3.93	2.900	0.496	17.1
Shank, l[a]	2.12 - 3.17	2.754		
Thigh, r	4.01 - 6.05	5.617	0.748	13.3
Thigh, l[a]	4.11 - 6.29	5.35		
Whole leg, r	6.65 -11.45	9.38	1.262	13.4
Whole leg, l[a]	6.75 - 9.95	8.86		

[a] Data on left leg are incomplete.

TABLE 4. VOLUME OF THE BODY SEGMENTS EXPRESSED IN PERCENTAGE OF THE WHOLE BODY (12 SUBJECTS)

Segment	Range	Mean	S. D.	C. V. in Percent
Hand	0.47- 0.62	0.566	0.052	9.20
Forearm	1.47- 1.72	1.702	0.112	6.58
Upper arm	2.98- 3.53	3.495	0.192	5.50
Whole arm	4.93- 5.79	5.73	0.299	5.22
Foot	1.04- 1.35	1.297	0.155	11.95
Shank	3.59- 4.30	4.083	0.276	6.77
Thigh	6.92-10.77	9.241	1.486	16.09
Whole leg	13.17-16.86	14.620	1.599	10.95

series of males. Table 5 gives similar values for the second series of males, and table 6 gives these values for females.

DENSITIES

As mentioned previously, it is very difficult to determine densities accurately. In table 7, the densities have been determined by the equations shown in the section III-B for males first series. The densities for both males and females, second series, have been determined by dividing the mass (weight) by the volumes derived by using the NYU and Skerlj formulas and by using Pascale's equations A and B and skin-fold thicknesses.

CENTER OF VOLUME

In the absence of satisfactory techniques for determining the center of mass, it has been assumed to be coincident with the center of volume. Table 8 shows the loca-

TABLE 5. VOLUME OF BODY SEGMENTS (MALE) EXPRESSED IN PERCENTAGE OF WHOLE-BODY VOLUME

Segment	Range	Mean	S. D.	C. V. in Percent
Hand, right	0.43- 0.59	0.50	0.051	10.2
Hand, left	0.42- 0.59	0.51	.049	9.61
Forearm, r	1.46- 2.01	1.69	.167	9.9
Forearm, l	1.36- 1.97	1.73	.184	10.6
Upper arm, r	1.95- 2.58	2.17	.222	10.25
Upper arm, l	1.80- 2.54	2.18	.273	12.5
Whole arm, r	3.98- 5.05	4.37	.195	4.47
Whole arm, l	4.12- 4.78	4.38	.339	7.75
Foot, r	1.13- 1.38	1.24	.111	8.95
Foot, l	1.13- 1.39	1.26	.076	6.03
Shank, r	4.14- 5.39	4.64	.429	9.25
Shank, l	3.47- 5.00	4.41	.475	10.77
Thigh, r	8.41-11.08	9.22	.819	8.89
Thigh, l	8.68-10.99	9.17	.723	7.88
Whole leg, r	13.98-16.60	15.09	.848	5.62
Whole leg, l	13.38-16.66	14.84	0.925	6.24

TABLE 6. VOLUME OF BODY SEGMENTS (FEMALE) EXPRESSED IN PERCENTAGE OF WHOLE-BODY VOLUME

Segment	Range	Mean	S. D.	C. V. in Percent
Hand, right	0.341- 0.600	0.497	0.087	17.5
Hand, left	0.320- 0.580	0.497	.082	16.5
Forearm, r	1.31 - 1.79	1.560	.137	8.8
Forearm, l	1.33 - 1.73	1.520	.132	8.7
Upper arm, r	1.70 - 2.40	1.955	.252	12.9
Upper arm, l	1.60 - 2.30	1.935	.263	13.6
Whole arm, r	3.59 - 4.80	4.00	.360	9.0
Whole arm, l	3.43 - 4.35	3.954	.314	7.94
Foot, r	1.17 - 1.70	1.31	.177	13.6
Foot, l		1.28		
Shank, r	4.40 - 5.95	5.18	.524	10.1
Shank, l		5.08		
Thigh, r	8.70 -10.80	9.87	.577	5.85
Thigh, l		9.72		
Whole leg, r	14.77 -17.80	16.42	0.921	5.61
Whole leg, l		16.10		

TABLE 7. WHOLE-BODY DENSITY

	Range	Mean Value	S. D.
Males, First Series			
Weight, kilograms	63.05 -87.77	73.42	7.572
Volume, liters (NYU)	56.70 -82.26	69.02	7.83
Volume, liters (Dupertuis)	58.43 -83.19	69.20	7.62
Density, kg/l (NYU)	1.029- 1.112	1.066	0.0247
Density, kg/l (Dupertuis)	1.049- 1.085	1.062	0.0122
Males, Second Series			
Weight, kilograms	64.87 -88.84	75.84	7.38
Volume, liters (NYU)	60.15 -84.70	70.83	7.43
Density, kg/l (NYU)	1.018- 1.063	1.045	0.0163
Density, kg/l (Skerlj)	1.023- 1.068	1.051	0.0145
Density, kg/l (Pascale A)	1.064- 1.080	1.074	0.0059
Density, kg/l (Pascale B)	1.054- 1.076	1.064	0.0068
Females, Second Series			
Weight, kilograms	42.775-69.710	59.790	7.67
Volume, liters	41.64 -67.22	56.42	6.94
Density, kg/l (NYU)	1.006- 1.124	1.049	0.0324
Density, kg/l (Skerlj)	1.004- 1.074	1.046	0.0214
Density, kg/l (Pascale A)	1.044- 1.076	1.063	0.0110
Density, kg/l (Pascale B)	1.062- 1.078	1.070	0.0054

TABLE 8. LOCATION OF MASS CENTERS FROM PROXIMAL JOINT IN PERCENTAGE OF SEGMENT LENGTH

Segments	Investigators				
	Harless	Braune & Fischer	Bernstein	Dempster	NYU
Entire arm	—	42.6	—	43.6	43.1
Upper arm	48.5	47.0	46.6	43.6	44.9
Forearm and hand	—	45.8	—	67.7[a]	38.2
Forearm	44.0	42.1	41.2	43.0	42.3
Hand	47.4	—	—	—	39.2
Entire leg	—	41.5	—	43.4	39.7
Thigh	46.7	44.0	38.6	43.3	41.0
Shank and foot	—	51.9	—	43.3	45.0
Shank	36.0	42.0	41.3	43.3	39.3
Foot (from heel)	46.0	43.4	—	43.3	44.5

[a] Distance from elbow to ulnar styloid is assumed to be 100%.

tion of mass centers (volume centers) obtained by various researchers. Some studies conducted on cadavers are probably more truly mass centers. Others, conducted on live subjects, are probably the centers of volume.

Table 9 has been prepared to provide information as to the location of the center of volume of the various body segments, measured from the proximal joint. Again, it should be noted that the values for the upper arm are measured from the axilla. In both tables 8 and 9, the value indicated is in percent of the segment length.

A study was conducted on seven above-knee amputees. There was considerable variation in the length and contour of the stumps, although all of them could be described as modified truncated cones. The average distance from the crotch, measured downward and expressed as a percentage of the total stump length, was 32.1%, with an upper limit of 44.0% and a lower limit of 23.0%. The standard deviation was ± 6.4%.

RADIUS OF GYRATION

The radius of gyration (p) is a distance measured from the true center of mass to a point within the mass at which, if all the mass were concentrated, its effect in rotatory movements would be similar to the effect of the mass as it is actually distributed. For geometrically similar shapes, the radius of gyration along a particular axis may be expressed as a percentage of the length of that shape along that axis.

It has been assumed that every body segment—arm, leg, upper arm, forearm—for one subject is geometrically similar to that of any other subject. If it were so, then the radius of gyration expressed in percentage of the length *(p/L)* should be relatively constant. It was found to be so, with minor variations. The values of *p/L* for the various body segments obtained by previous researchers and in the first NYU study are given in table 10. Values for the second NYU study are given in table 11.

Table 12 has been included as a guide against which the computed values of *p* may be compared. This table indicates the average values of *p* (the radius of gyration) for the populations included in the second series of NYU studies; not all values were determined for each category, and the table reflects this. The results were computed on the basis of tests and measurements were made as previously described.

TABLE 9. LOCATION OF CENTERS OF VOLUME MEASURED FROM THE PROXIMAL JOINT EXPRESSED IN PERCENTAGE OF SEGMENT LENGTH

Segment	Normal Males	Normal Females	Hemiplegics, Amputees and/or
Upper arm, right	46.4	46.9	45.8
Upper arm, left	46.0	45.9	46.4
Forearm, r	41.9	43.4	42.4
Forearm, l	42.2	43.5	42.4
Hand, r			30.7
Hand, l			30.1
Thigh, r	43.7	42.1	
Thigh, l	43.4	42.5	
Shank, r	42.0	42.6	
Shank, l	41.5	41.3	
Foot, r[a]	58.9	57.6	
Foot, l[a]	59.5	58.0	

[a] These values are measured vertically down from the ankle joint.

DISCUSSION

The data may be used in a number of ways. Consideration must be given to the nature of the problem for which a solution is sought and the accuracy desired. If a situation exists where a prosthesis or orthosis is desired for a specified individual, it would be best to obtain data directly on the individual. In such a case, judgment should be made as to which of the various techniques available would be adapted best to the set of conditions present, i.e., the condition of the subject, the skills of

TABLE 10. RATIO (C_3) OF RADIUS OF GYRATION (ρ) TO SEGMENT LENGTH (L)

Segment	Braune & Fischer: 1 cadaver Test I, R	Braune & Fischer: 1 cadaver Test I, L	Braune & Fischer: 1 cadaver Test II, R	Braune & Fischer: 1 cadaver Test II, L	NYU: 8 living subjects	Weighted Average
Entire upper extremity	—	—	0.30	0.31	0.24	0.252
Upper arm	0.27	0.27	.29	.31	.26	.268
Forearm and hand	.26	.28	.29	.32	.25	.263
Entire lower extremity	—	—	.32	.32	.24	.256
Thigh	.26	.27	.31	.31	.23	.250
Shank and foot	.32	.32	.33	.35	.29	.303
Shank	.25	.26	.24	.26	.27	.264
Mean	0.27	0.28	0.30	0.31	0.25	0.265

TABLE 11. RATIO OF RADIUS OF GYRATION (ρ) TO SEGMENT LENGTH (L) IN PERCENTAGE

Segment	Range	Mean	S. D.
Whole arm (normals)	24.2–26.0	25.0	0.79
Whole arm, males	24.0–26.0	24.9	0.93
Whole arm, females	24 –26	25.1	0.60
Whole arm, male amps.	24 –27	25.9	0.99
Whole arm, female amps.	24 –27	25.2	0.69
Whole arm, all amps.	24 –27	25.6	1.04
Whole arm, hemiplegics	25 –27	25.8	0.75
Upper arm, all amps.	19 –36	27.2	4.85
Forearm, all amps.	27 –31	29.2	1.23
Hand, all amps.	26 –29	26.7	0.67
Whole leg, males	31 –33	31.8	0.63
Whole leg, females	28 –30	29.6	0.73
Thigh	27 –29	28.1	0.74
Shank	27 –29	28.1	0.70
Shank & foot	32.0–34.0	33.4	0.66

TABLE 12. AVERAGE VALUES OF RADIUS OF GYRATION ρ FOR VARIOUS POPULATIONS, IN INCHES

	Normals	Amputees	Hemiplegics	All	Low	High
Females						
Whole arm	16.97	17.62	18.33	17.40	15.18	19.05
Upper arm		8.29	8.33	8.30	6.15	10.50
Forearm		7.22	7.96	7.51	6.48	8.01
Hand		4.27	3.83	4.09	3.47	4.34
Whole leg	22.95	23.10	24.69	23.15	21.03	25.05
Thigh				10.38	9.30	11.45
Shank				10.91	9.62	12.27
Shank & foot				15.45	13.99	16.92
Males						
Whole arm	18.28	19.89	19.85	19.13	17.62	21.06
Upper arm		9.36	8.77	9.17	7.85	11.10
Forearm		7.93	8.11	7.99	7.32	8.73
Hand		4.67	4.34	4.56	4.02	5.36
Whole leg	25.14	24.59	24.86	24.96	23.49	26.81
Thigh				10.31	9.38	11.67
Shank				11.87	11.50	12.12
Shank & foot				16.41	15.95	17.00

available personnel, and the facilities available.

When extreme accuracy is not required, or in cases when the problem is confined to a class of individuals, or the solution may have a general application, the data may be used in various ways, with differing degrees of accuracy. In successively decreasing order of accuracy, the following maybe done:

1. Obtain the weight and height of the subject and the length and circumferences of the segments under consideration; use tables and graphs judiciously and, where several sets of data are available, use the most appropriate.

2. Obtain weight and height of the subject only and use tables as suggested.

3. Obtain weight and height of subject and use average data only. Data may be used for determining the length of a segment, its volume, mass, center of volume, center of mass, radius of gyration, and moment of inertia.

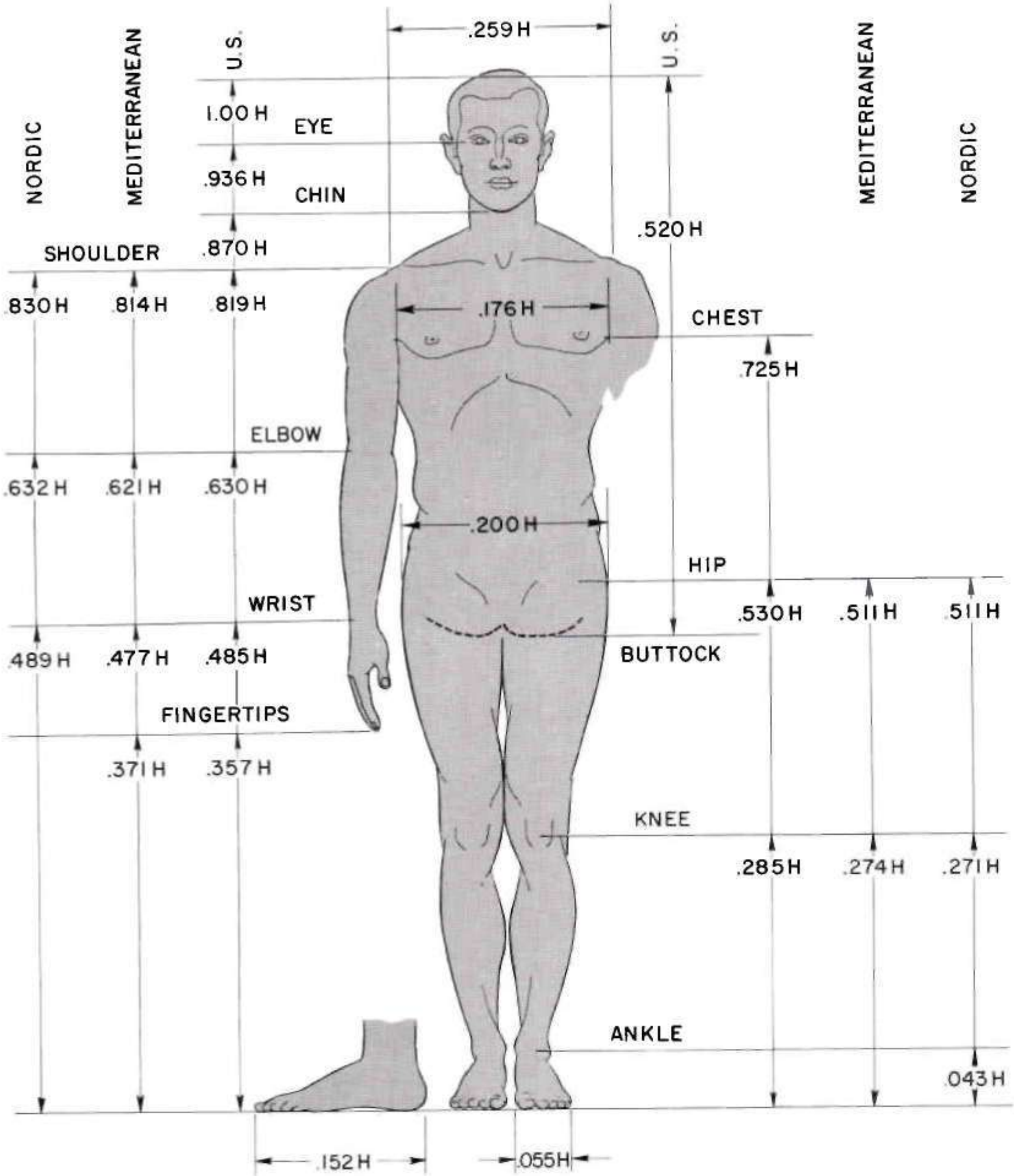

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Fig. 7.

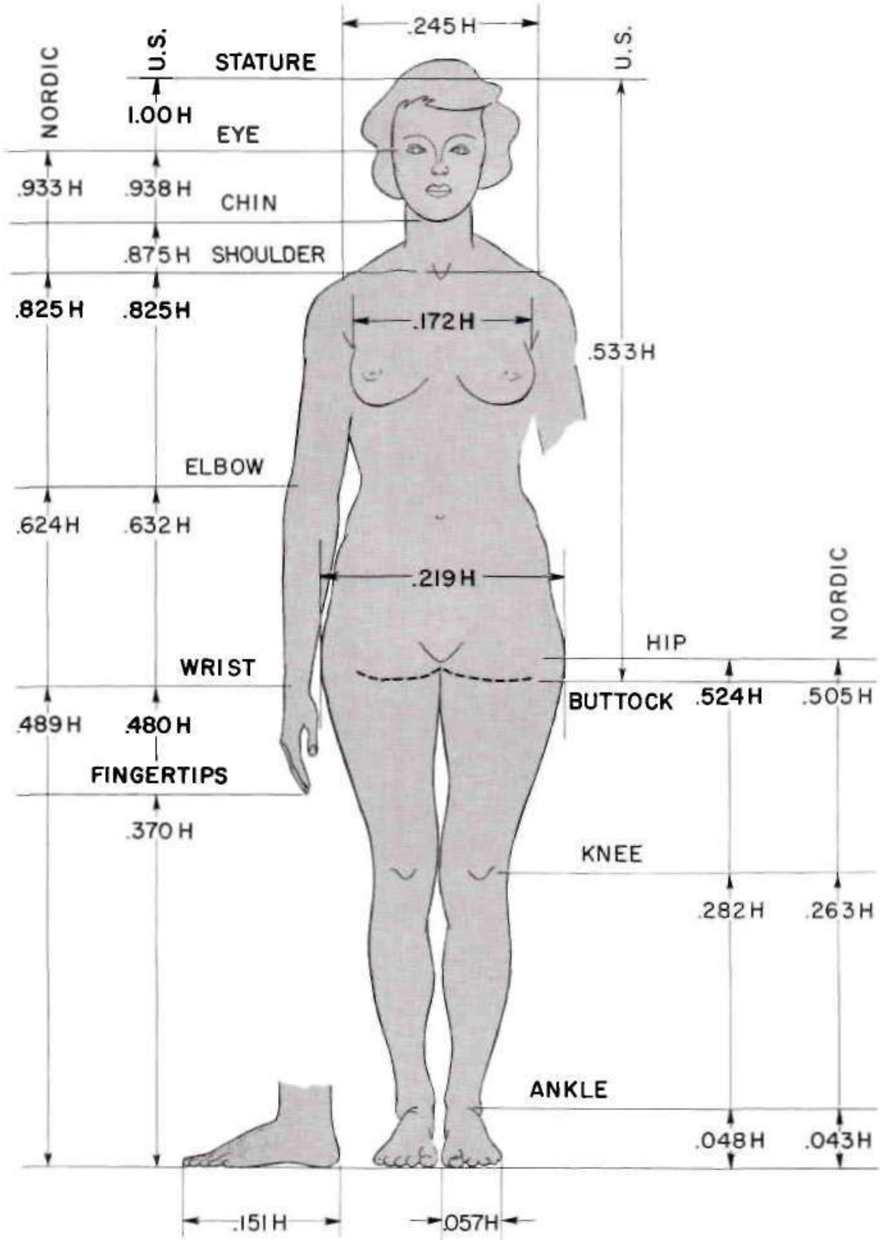
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Fig. 8.

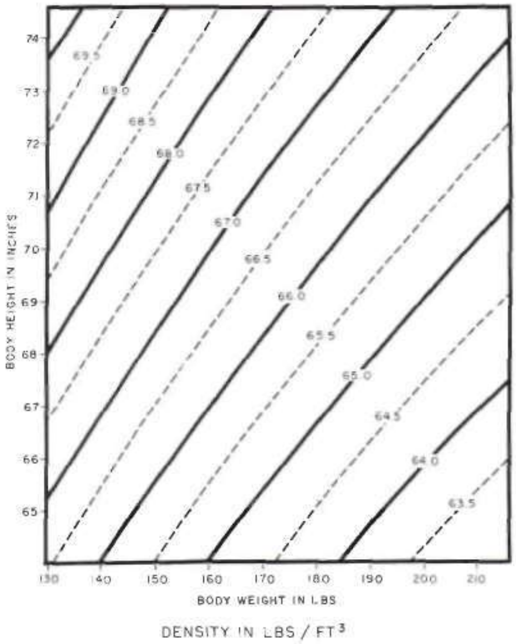


Fig. 9.

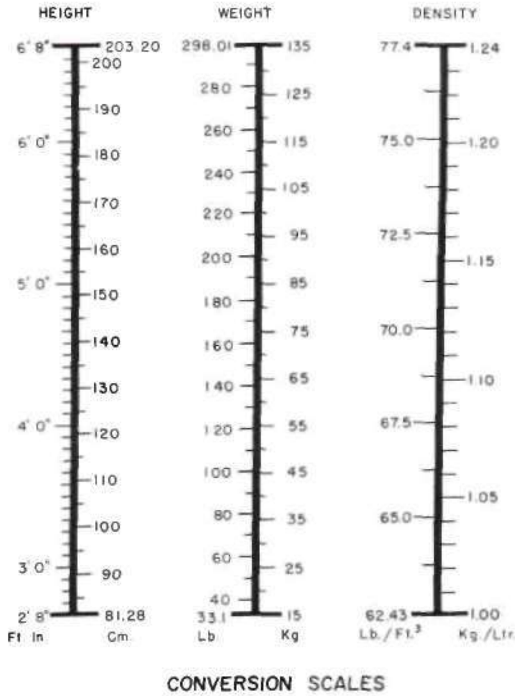


Fig. 10.

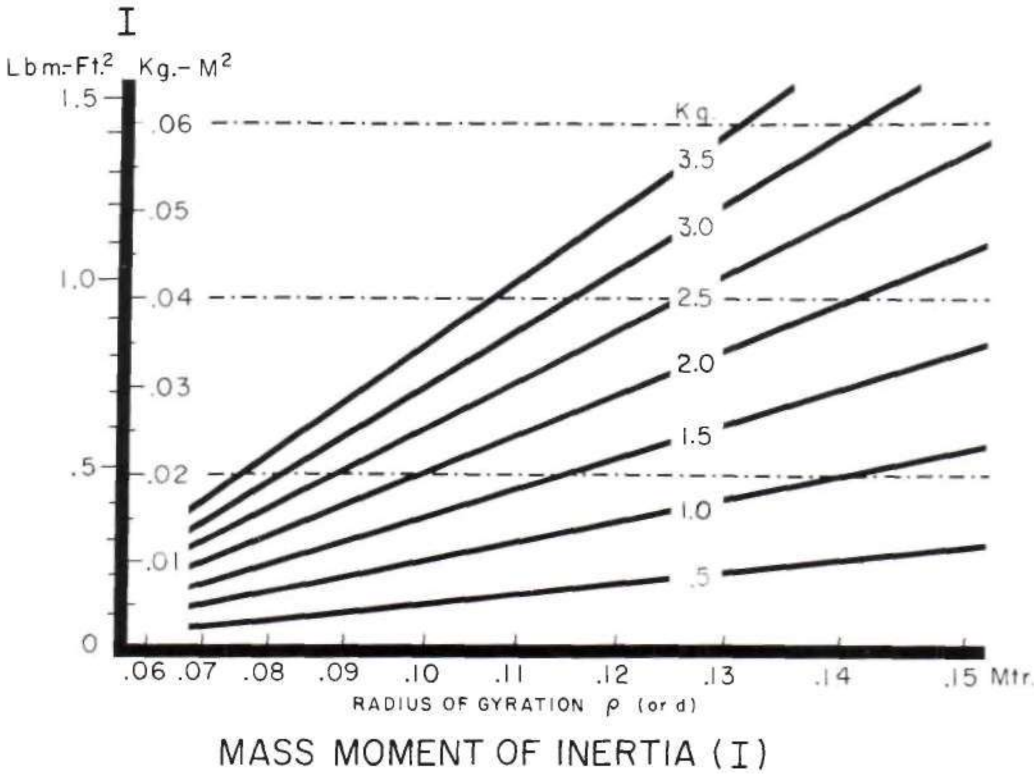


Fig. 11.

SAMPLE COMPUTATION

To determine the mass moment of inertia of the upper arm, forearm, and hand for a male patient (possibly for application of an externally powered orthosis), only the height and weight of the subject need be known.

Procedure

If the subject weights 190 pounds and is 73 inches in height:

1. On graph (fig. 1), join the weight in pounds (190) to the height in inches (73) by a straight line. At the intercept of this line with line c a value for c, approximately 12.8, is obtained.

2. On graph (fig. 2), locate c = 12.8, proceed vertically upward to intersect solid black line, then proceed horizontally from this point to determine the value of whole-body density *d:*

d = 66.8 pounds per cubic foot

3. On graph (fig. 4), proceed as in (2), from *d* = 66.8 vertically downward to intersect lines of segment densities:

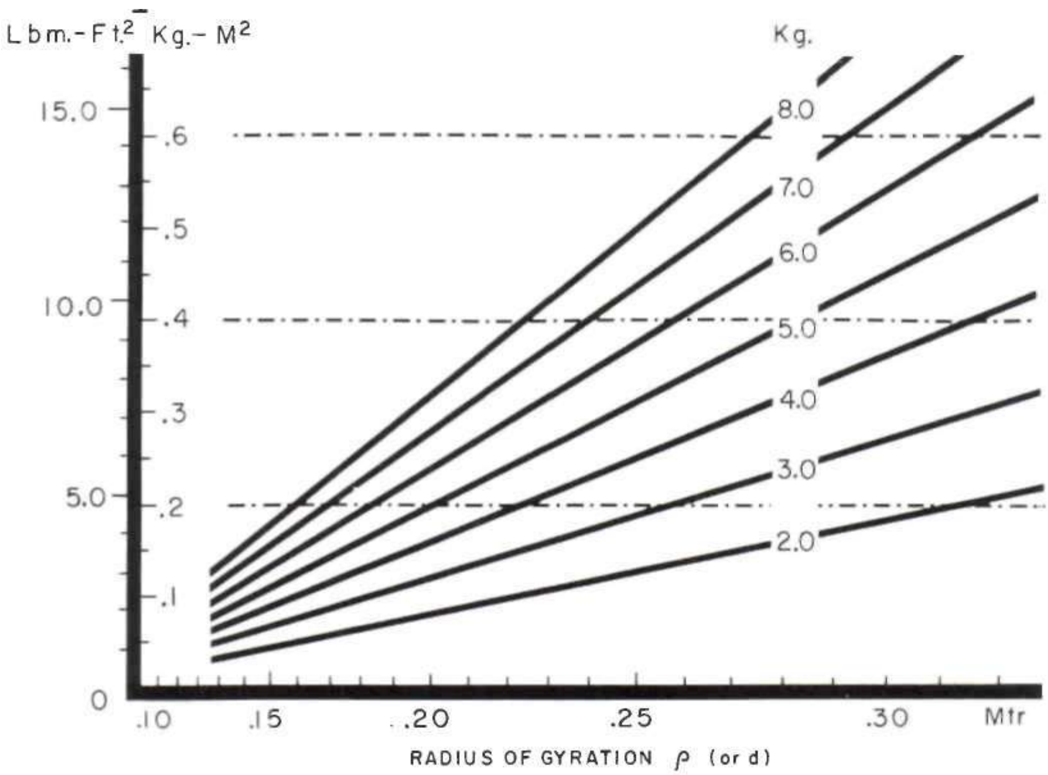
d, upper arm = 68.1 lb/ft^3
d, forearm = 70.7 lb/ft^3
d, hand = 72.2 lb/ft^3

4. Given the weight of 190 pounds and whole-body density of 66.8 pounds per cubic foot, we may compute whole-body volume:

190/66.8 = 2.85 cubic feet

5. Table 4 gives values of volume for body segments in percentage of whole-body volume:

volume, upper arm
= 3.495 x 0.01 x 2.85 = 0.0995 ft^3



MASS MOMENT OF INERTIA (I)

Fig. 12.

volume, forearm
$= 1.70 \times 0.01 \times 2.85 = 0.0485\ ft^3$
volume, hand
$= 0.566 \times 0.01 \times 2.85 = 0.0161\ ft^3$

6. Multiplying the volumes of the segments by their respective densities, the mass (or weights) of the segments are obtained:

m (w), upper arm = 0.0995 x 68.1 = 6.78 lb
m (w), forearm = 0.0485 x 70.7 = 3.43 lb
m (w), hand = 0.0161 x 72.2 = 1.16 lb

7. To obtain the approximate lengths of the body segments when they have not been measured, figures 7 and 8 may be used. The mean lengths expressed in terms of body height are 0.189*H*, 0.145*H* and 0.128*H* for the upper arm, forearm, and hand respectively. The lengths then are:

$L_v = 0.189 \times 73 = 13.8$ in.
$L_f = 0.145 \times 73 = 10.6$ in.
$L_h = 0.128 \times 73 = 9.35$ in.

8. Having obtained the lengths of the segments, the location of the center of

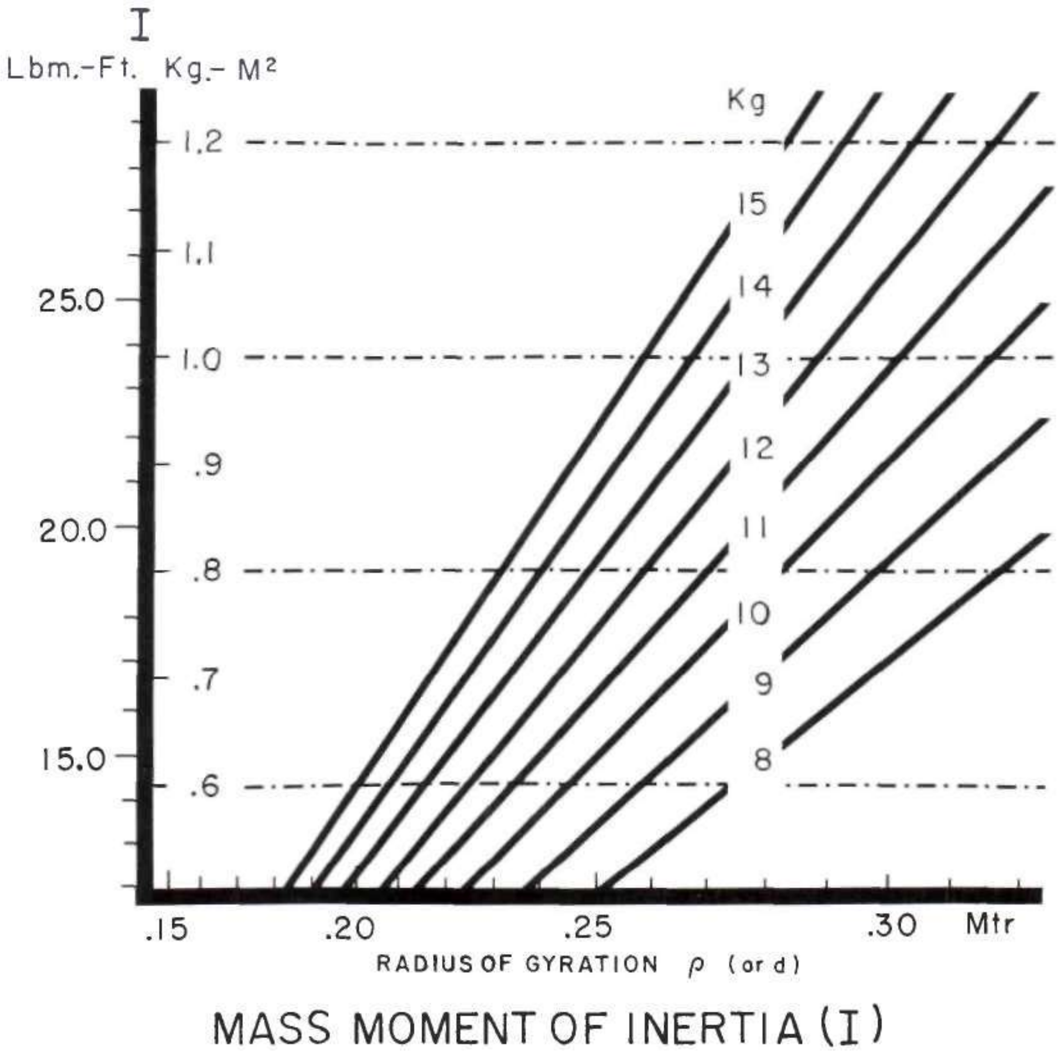


Fig. 13.

volume (mass) can be determined using values given in tables 8 or 9:

c, upper arm = 0.461 x 13.8 = 6.37 in.
c, forearm and hand = 0.420 (10.6 + 9.35) = 8.38 in.

9. The radius of gyration (p) for the segments may be obtained using the values in tables 10 or 11:

p, upper arm = 0.268 x 13.8 = 3.70 in.
p, forearm and hand - 0.263 x (10.6 + 9.35) = 5.25 in.

10. The moment of inertia about its proximal axis of rotation is expressed by the equation:

$$Ij = m(pp + cc)$$

The moment of inertia of the upper arm about the shoulder:

$$I_{J_u} = 6.78 \text{ lbs. } (\overline{6.37 \text{ ins.}}^{\,2} + \overline{3.70 \text{ ins.}}^{\,2}) = 368 \text{ lbs. ins.}^2 \quad [11]$$

The moment of inertia of the forearm about the elbow:

$$I_{J_f} = (3.43 + 1.16) \text{ lbs. } (\overline{8.38 \text{ ins.}}^{\,2} + \overline{5.25 \text{ ins.}}^{\,2}) = 449 \text{ lbs. ins.}^2 \quad [12]$$

If the moment of inertia of the forearm and hand about the shoulder joint is desired, then the equation is:

$$I_{J_f} = (3.43 + 1.16) \text{ lbs. } [\overline{5.25 \text{ ins.}}^{\,2} + (8.38 + 13.8) \text{ ins.}^2] = 2380 \text{ lbs. ins.}^2 \quad [13]$$

Figures 9 through 13 have been included to facilitate any computations, to ease conversion from metric to British systems of measurement, and for graphically determining the moments of inertia.

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