

Determination of Body Segment Parameters₁

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This paper describes methods presently being used by the Research Staff of New York University to evaluate the important parameters of human body segments: mass, volume, center of mass and mass moment of inertia. Previous studies in the field are reviewed with regard to data obtained and subjects used in the investigations. Sources of difficulty in the proper solution are discussed in order to formulate the best procedure, followed by a description of the techniques now being employed. The paper concludes with a look into future applications of body segment parameter data.

INTRODUCTION

Purpose of the Investigation

The experiences of the past 15 years have shown that a proper development of prosthetic and orthotic devices, tools and entire man-machine systems requires a thorough understanding of the biomechanical principles of human motor performance.

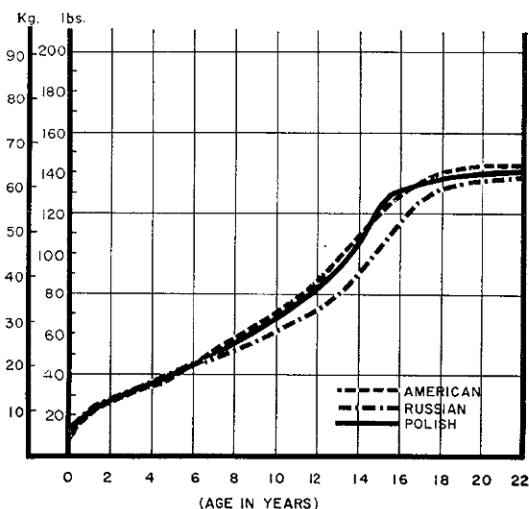
The knowledge of a person's body segment parameters (e.g. mass, volume, center of mass, mass moment of inertia) would permit an analysis of his motor activity to be made and thus point out how he may perform his motor functions more efficiently. He could be fitted with a better brace or artificial limb; his body segment growth could be examined in both normal and pathological cases and comparisons made; the tools he uses could be made more efficient and safe. In short, the human organism could be made a more comfortable and a more effective performer.

Statement of the Problem

Data on body segment parameters have not been readily obtainable. Such facts as are available are easily misinterpreted because of their inherent limitations. The data that are presently available in this country are based mainly on measurements made on cadavers of

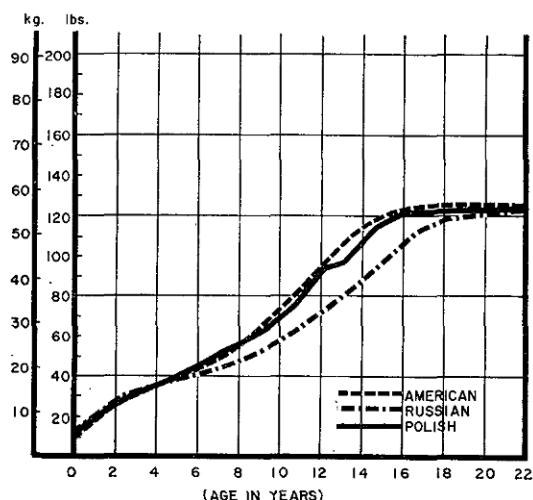
advanced age and below-average height and weight. These can hardly be considered as valid data for a normal, living population sample; for we know that body parameters are significantly influenced by such factors as body build, age, sex, ethnic origin and disease. A good illustration of this influence is shown in Figs. 1 and 2, where comparisons are made of the weights of boys and girls as a function of age and nationality. The graphs were constructed by the Research Staff of New York University using data obtained from studies made on American, Russian, and Polish young people.

It is desired to obtain body parameter data for as wide a population sample as possible



BOYS' BODY WEIGHT
Fig. 1.

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GIRLS' BODY WEIGHT

Fig. 2.

with maximum accuracy. Further, these subjects will have to be classified according to body build by some form of body typology, such as the somatotyping procedure of Sheldon *et al.* (1940), so that a tabular relationship between body parameters and body build can be developed. It is assumed that when simple anthropometric measurements of a person are made the body segment parameters then can be easily determined.

In this paper, the previous studies in this area will be briefly reviewed. Then methodology and difficulties in solution will be discussed and finally the intended new techniques will be described.

PREVIOUS STUDIES

Body segment parameter studies were begun over 100 years ago by Harless (1858) in Germany. He published a textbook of plastic anatomy and in 1860 a treatise, *Die Statistischen Momente der Menschlichen Gliedmassen*, which launched many studies into body segment mass, volume, center of mass and mass moment of inertia.

Most notable of these investigations are those performed by Meeh (1895), Braune and

Fischer (1889), Bernstein (1931), Zook (1932) and Dempster (1955). Braune and Fischer based their final data on three cadavers whose height and weight approximated those of the average German soldier. Dempster tabulated results on eight cadavers, while Harless worked with two decapitated cadavers for his body parameter studies. The data of Braune and Fischer and Dempster are reported in compact form by Duggar (1962). While evaluating the data, it is necessary to remember that (1) cadavers, not the living, were studied; (2) these cadavers were of advanced age and of below-average height and weight; and (3) a limited number of subjects was used.

Meeh (1895) in Germany determined the body volumes of ten living subjects, eight males and two females, ranging in age from 12 to 60 years. In order to find segment mass, he obtained a value for the specific gravity during quiet respiration and found, contrary to the conclusions of E. Boyd (1933) that density showed no increase with age.

A very thorough study of how segment volumes vary with age was made in 1930 by Zook. His sample consisted of 164 boys aged five to nineteen years and he made extensive use of the immersion method of finding body volumes (to be described later). Zook's claim that his method permits a direct determination of the specific gravity of a particular body segment to be made does not appear to be conclusively proven.

In the 1930's, N. Bernstein and his co-workers in Russia determined the masses, centers of mass and mass moments of inertia of a large sample of male and female subjects. Unfortunately the monograph on mass center location and mass of the living human links with the results of this study is not available in the United States. However, excerpts of the data obtained were published by Bernstein in a book, *Work Physiology* (in Russian), by Konradi, Slonim and Farfel in 1935. These data were on 152 living subjects (76 males, 76 females) within the ages of 10 and 75 years. From the results and descriptions available, it would seem

that this information is the most accurate to date. Nevertheless, it is obvious that the results are applicable only to the Russian population.

It is evident that in practice there exists a definite need for a simple method of body segment parameter determination of living subjects. This method should be based on the results obtained with a sufficiently large and diverse population sample so that the method will be applicable to all persons in biomechanical studies.

GENERAL METHODOLOGY

In order to obtain the proper data, a large population sample of varying age and body build is a primary prerequisite. However, one must be equally cognizant of the many other important factors that contribute to, or detract from, the valid solution.

Difficulties in the Proper Solution

In the commonplace technical area, where it has been necessary to evaluate the volume, mass, center of mass, etc., of an inanimate object, this object is usually one of fixed dimensions; that is, there is no involuntary movement of parts. The living human organism, on the other hand, is totally different in that none of its properties is constant for any significant period of time. There are differences in standing erect and in lying down, in inhaling and in exhaling, in closing and in opening the hand. It is necessary, therefore, to develop a procedure of measurement which can contend with these changes, and to evaluate data with particular reference to a specified orientation of the body.

One ever-present problem in dealing with the body is the location of joints. When a segment changes its attitude with respect to adjacent segments (such as the flexion of the elbow), the joint center, or center of rotation shifts its position as well. Thus, in obtaining measurements on body segments, it is necessary to specify exactly what the boundaries are. As yet,

there is no uniformly accepted method of dividing the body into segments.

Another source of error is due to the elasticity of skin, muscle and other tissues. For example, a person's height will differ according to his orientation. It will be less when standing than when supine due to compression of the tissues. It is important to conduct one's test while avoiding unnecessary contractions or extensions of the soft tissue.

In the determining of the mass of body segments of the living subjects, some previous investigators have resorted to measuring the volume and applying a known value for density, which is the proportionality constant between mass and volume. In doing this, one must be aware of the fact that density is not constant in a body. The volume of the trunk changes continually with breathing, and density of all other parts of the body changes with the movement of the body fluids. In working with humans, changes due to breathing usually are unavoidable; hence, it is necessary to keep the subject's respiratory excursions at a minimum during the test.

One must always contend with the physiological nuances of the human organism, body sway, static tremor, etc. One may also encounter psychological difficulties with the test subject. His natural modesty may inhibit his otherwise innate reaction to test stimuli; for example, posing in the nude for anthropometric studies may result in an uncommon tenseness of the muscles, giving erroneous results.

It is therefore essential that the method chosen for measurement does not extend already existing discrepancies in the human organism and does not produce undesirable reactions in the subject.

Methods that Can Be Used

In selecting a method for use on living subjects, one must consider certain pertinent factors. First, movement of the subject, both of the segment in question and of the remainder of his body, should be avoided where possible. The subject should be comfortable during the

procedure so as to give a natural reaction to a stimulus. Second, the so-called "signal-to-noise" ratio should be kept as high as possible; that is, the numerical value of the parameter desired should be high with respect to that of the tare associated with the test apparatus. Third, many of the measurements may fluctuate even while the data are being taken because of breathing, body sway, and other factors. An effort should be made to obtain a mean value from the varying data. This usually can be done by electrical means, such as the use of a linear variable differential transformer attached to the beam of a balance scale to measure weight.

Many measurements will be taken on a particular body segment and an average value will be found to indicate the result. Particular attention must then be paid not only to the mean value but also to the deviation of the series of measurements from the mean. Should the standard deviation of a particular set of results be large, one should not consider the mean value as a good, representative figure for the segment parameter.

In light of the above factors, and after studying the works of the previous researchers, the Research Staff of New York University has developed procedures and equipment for studying and evaluating body segment parameters of the living. These methods will now be discussed.

PRESENT STUDIES

Method of Coefficients

Most of the already tabulated data have been obtained by the method of coefficients. In this technique, fixed relationships were established using cadaver measurements whereby making a simple anthropometric measurement on the subject allows his segment parameters to be found. There are three such relationships in the form of ratios called *coefficients*. One coefficient C_1 , is the ratio of segment mass to whole body mass; the second, C_2 , is the ratio of the distance between the mass center of the segment and the proximal joint to the total segment length; the ratio of the radius of gyration of the segment about the medio-lateral centroidal axis to the total segment length is the third coefficient, C_3 . These coefficients were tabulated by Harless (1860) and later used by Braune and Fischer (1890) as well as Bernstein (1931) and Dempster (1955) so that measurement of the whole body mass and segment length is all that is needed to find segment mass, center of mass and mass moment of inertia (equal to mass times the radius of gyration squared).

Some samples of these coefficients are shown in Tables 1, 2 and 3. An extension of the above three coefficients is C_4 , evaluated by Fischer, which is the ratio of the radius of gyration with respect to the longitudinal axis of the segment

TABLE I
Body Segment Weight as Per Cent of Total Weight
(Males Only)

	<i>Investigator</i>				
	<i>Harless</i>	<i>Meeb</i>	<i>Braune and Fischer</i>	<i>Bernstein</i>	<i>Dempster</i>
Head, neck and trunk					
less limbs	53.42	59.08	49.68	52.98	56.50
Upper arms	6.48	6.19	6.72	5.31	5.30
Forearms	3.62	3.38	4.56	3.64	3.10
Hands	1.68	1.46	1.68	1.41	1.20
Thighs	22.36	17.36	23.16	24.43	19.30
Shanks	8.78	9.35	10.54	9.31	9.00
Feet	3.66	3.18	3.66	2.92	2.80

to the total segment length. Thus we have the radii of gyration about the lateral and longitudinal axes. To find the radius of gyration, r , with respect to an arbitrary axis making an angle ϕ with the longitudinal axis, the equation is

$$r = \sqrt{(C_3^2 L^2 \sin^2 \phi + C_4^2 D^2 \cos^2 \phi)}$$

where L is the total segment length and D is the mean diameter of the segment in the plane through the mass center and perpendicular to the longitudinal axis.

TABLE 2

Body Segment Weight as Per Cent of Total Weight

	<i>Investigator</i>			<i>Fischer (3 Male cadavers)</i>
	<i>Bernstein (living subjects)</i>			
	<i>76 Male</i>	<i>76 Female</i>	<i>Average</i>	
Upper arms	5.31	5.20	5.26	6.72
Forearms	3.64	3.64	3.64	4.56
Hands	1.41	1.10	1.26	1.68
Thighs	24.43	25.78	25.11	23.16
Shanks	9.31	9.68	9.49	10.54
Feet	2.92	2.58	2.75	3.66

TABLE 3

Mass center to proximal joint relative to segment length

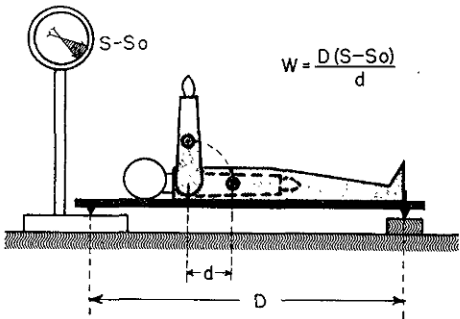
	Investigator			
	Harless	Braune and Fischer	Bernstein	Dempster
Upper arm	0.485	0.470	0.466	0.436
Forearm	0.440	0.420	0.412	0.430
Thigh	0.467	0.440	0.386	0.433
Shank	0.360	0.420	0.413	0.433

Excepting Bernstein's data, the coefficients were obtained from measurements made on a limited number of dissected cadavers with the assumption that the ratios would prevail also in living subjects. We must therefore question the accuracy of these data. From the results given in the tables it is evident that

discrepancies in coefficients exist between each investigator. Since only Dempster gives anthropological information on the body build of his subjects, it is difficult to draw any definite conclusions about how these coefficients vary with body typology.

Determination of Mass

In order to evaluate the mass of the living body segment, the principle of moments or of the lever is utilized. This procedure, called the method of reaction change, is described by Drillis (1959). It is based on knowledge of the mass center or center of gravity (c.g.) of the segment, a parameter which can be found by methods described later in this article. The subject is placed on a board supported by a fixed base at one end and a weighing scale at the other. Two scale readings are taken for two different orientations of the segment in question. Knowing the change in the segment c.g. position and the span length of the board, one can find the segment weight. An illustration of this procedure is shown in Fig. 3.



DETERMINATION OF ARM WEIGHT
OF A LIVING SUBJECT

- W- WEIGHT OF ARM IN LBS.
- S-S0-DIFFERENCE OF REACTION
FORCE IN LBS.
- D-DISTANCE BETWEEN SUPPORTS
- d-DISPLACEMENT OF CENTER OF
GRAVITY OF ARM

Fig. 3.

Determination of Volume

Mass may also be found by finding volume and applying the factor of density as several researchers have done. There are at present various methods of determining body segment volumes of the living. Basically, these can be divided into three techniques:

- (1) Immersion or water displacement.
- (2) Segment zone or computational methods.
- (3) Mono- and stereo-photogrammetry.

The first is a familiar procedure that is simple in theory. The second is a more intricate method where great accuracy is obtained only through a good deal of work. The last is as yet an untried procedure but which promises good results in view of the work already done with inanimate objects using this method.

Method of segment immersion. A procedure for segment volume determination of the living has been described by Dempster (1955). It involves the construction of devices containing water designed so as to accommodate the insertion of a limb, with a surrounding jacket to catch the water caused to overflow as the limb is immersed. This surplus water may be measured to determine its volume, hence the volume of the immersed limb.

In an effort to improve on this technique, a method similar in principle has been devised by the Research Staff of New York University. This is illustrated in Fig. 4. In this case, the particular segment, (shown here as the arm), with boundary landmarks for immersion levels suitably indicated, is placed in an empty tank. The other tank (the upper one in the illustration) is then filled with a known volume of water. Water from this tank is then used to fill the lower tank to the desired level (e.g. the elbow) and readings are taken from the vertical scales indicating the amount of water removed from the supply tank and the volume that the water (containing the arm segment) occupies in the lower tank. The difference between these two values is the desired segment volume.

The lower tank may be filled in incremental steps, the scale readings corresponding to volumes since the tanks are of known diameter. It is felt that this immersion procedure is a more desirable one for many reasons than that previously described. The subject can assume a comfortable position which he can maintain

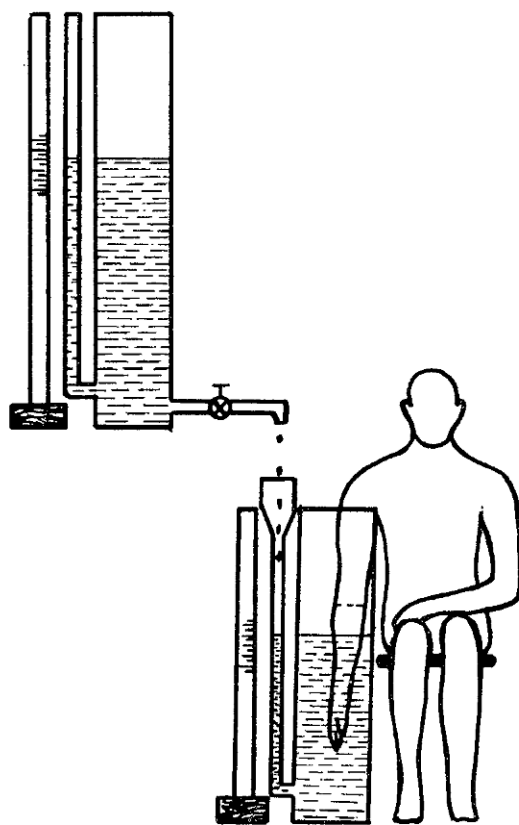


Fig. 4. Segment immersion method.

for the duration of the test. There is no motion of his body required so as to keep metabolic influences at a minimum. In addition, readings may be taken quickly and accurately at any time, as opposed to the overflow method where it is necessary to remove the overflow water and weigh it separately to determine its volume.

The immersion technique can be applied to the study of the whole body volume but great accuracy cannot be expected. The subject

must be properly trained in the procedure, and account must be taken of the air in the lungs. If measurement of displaced water is too difficult, the same end may be achieved by measuring the hydrostatic loss in weight of the subject. In either case, this is not an easy procedure.

Segment zone method. The basic principle behind this procedure is that the whole equals the sum of its parts. The parts are formed by subdividing the body segment into zones of equal height by tracing circumferences on the segment at known distances from the proximal joint. The cross-sections of the segment which form the boundaries of the zones may be approximated as to their geometric shape, i.e., circular or elliptical, and thus by measuring the circumference of the segment at each cross-section, the areas may be determined. Since the zone heights have already been selected, the volume of each zone can now be found by assuming a particular regular solid shape for the zone (cylindrical, conical or spherical). Thus, in order to find the entire segment volume, these individual zone volumes are summed up over the segment length.

The pertinent geometrical formulae for area and volume are available in a variety of technical handbooks. In addition, Harless (1860) and Amar (1914) have published formulae specifically for finding total volume of the segments. The accuracy of the result depends on the zone length postulated—the smaller the height, the closer the geometric assumption will be to the actual segment configuration. There are, of course, practical limitations to this zone height, and great care must be taken in measuring circumferences. In cases where the segment configuration lends itself, the whole segment may be considered a zone with circumferences taken at the proximal and distal joints to give a rough approximation to the segment volume. In some segments, such as the forearm, this figure may have considerable accuracy.

Photogrammetry. The basic notion of this method is essentially that used in developing

contour maps in aerial photography. It consists of projecting levels of constant elevation onto the subject which will divide the desired segment into zones much like the segment zone procedure discussed above. As an example, observe the results of projecting vertical lines onto the profile of an erect human to give a contour "map" in the rear view in Fig. 5. The portion of the body contained between two contour levels corresponds to a segment zone bounded by two flat areas. In order to produce these zones on the body and to subsequently measure their volumes, optical methods are employed.

The contour levels are produced by constructing a gridwork of transparent colored tapes placed parallel and at a known separation on a sheet of clear glass. Thirty-five millimeter transparencies are made from these grids and inserted into slide projectors of long focal length on both sides of the subjects, thereby casting a colored shadow onto the segment. When observed from the front, the contours are clearly visible.

In order to determine the volume of the segment, the volume of each zone must be determined. For example, if the segment is spherical, it can be assumed that the zones are frustums of a cone, the volume of which can be found by determining the areas of the circles bounding the zone since the height of the frustum is known. In the general case, the zone boundary planes will not be circles but irregular shapes whose areas can be determined only by construction methods. In order to accomplish this, the segment is photographed in the view showing the contour areas normal to the camera axis. The areas may now be measured from this photograph using the polar planimeter. The procedure is well-described by Wild (1954), who gives an equation allowing a quick determination of the desired segment volume.

A controlled experiment by Pierson (1959) demonstrated the accuracy of volume determination by photogrammetric methods. He examined four techniques of finding the volume of a basketball using water displacement as the

control method. The results of his study showed that the error between the value for volume as found by photogrammetry and that found by water displacement was only 1.2 per cent, certainly a desirable figure.

In order to determine the usefulness of the photogrammetric technique in measurement of the living, Hertzberg, Dupertuis and Emanuel (1957) photographed living subjects and took

of the object. The two photographs may be juxtaposed in viewing so that the proper sensation of depth is achieved. This would compensate for the parallax variation inherent in the one-camera system.

A further study was conducted on the photogrammetric method which indicates that this technique is a desirable one. Tanner and Weiner (1949) studied the reliability of this

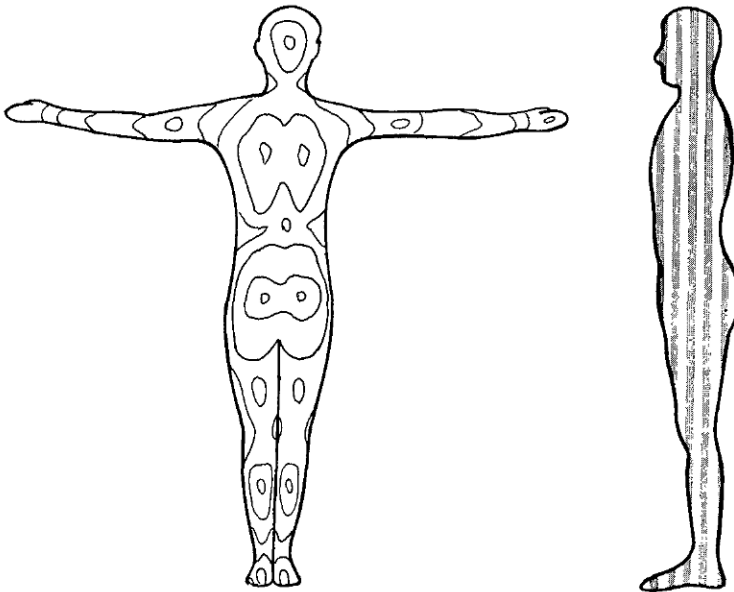


Fig. 5. Contour mapping of the body.

anthropometric measurements from the photographs. These data were then compared with the same measurements made directly on the living subjects and this comparison revealed a discrepancy that was generally less than one per cent; the greatest error, occurring in the waist circumference measurement, was only 1.25 per cent.

In addition, Hertzberg *et al.* describes a further variation of this method called Stereophotogrammetry. Here, instead of one camera photographing the object, two stereo cameras are used, each offset from the normal line to the subject, to provide a binocular view

procedure, that is, the repeatability of photogrammetric measurements from one occasion to another. After employing variations in their procedure on seventy subjects, they concluded that photogrammetric measurements are in general as reliable as measurements taken on the living. The pose of the subject for photogrammetric pictures, according to Dupertuis and Tanner (1950) should be standardized.

Where procedures such as water displacement are impractical and/or undesirable, for example in determining the volume of the head, the photogrammetric technique should be used. In addition this method requires a

minimum amount of the subject's time, a factor which is significant in the study of large population samples.

Determination of Center of Mass

Evaluation of the center of mass is divided into two categories: mass centers of body segments and mass center of the whole body. Establishment of the former parameters will be considered first; the methods that are used are based on the segment zone technique and on the compound pendulum theory.

Segment zone method. The guiding principle in this procedure is the result of a study conducted by Bernstein *et al.* (1931) on frozen cadavers. He concluded that for the required accuracy, the center of mass of a body segment can be considered coincident with the center of volume. One of Bernstein's co-workers, Salzgeber (1948), divided the particular body segment into zones of equal volume and then determined the corresponding heights by successive immersion of the segment to the zone levels. Assuming a geometric form for the zones, one can develop a mathematical formula for finding the segment volume center, and hence the mass center. Such an equation is available in the Salzgeber's paper.

Compound pendulum method. The technique of considering the body segment as a compound pendulum, that is, a distributed mass freely suspended from a point (say, the proximal joint), has been primarily developed to measure the mass moment of inertia of the segment. In order to find the moment of inertia, it is necessary to know the effective point of suspension and the center of mass of the segment as well, thus there are three unknown quantities. A study by Nubar (1960) found that these unknowns may be obtained if it is assumed that the restraining moment generated by the individual is negligible. In order to simplify the calculations, any damping moment (resulting from the skin and the ligaments at the joint) is also neglected. The segment is then allowed

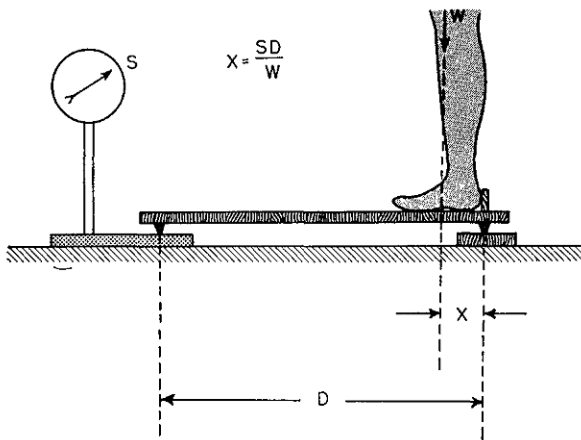
to oscillate, and its period, or time for a complete cycle, is measured for three cases: (1) body segment alone, (2) segment with a known weight fixed to it at a known point, (3) segment with another known weight fixed at that point. Knowing these three periods and the masses, one can find the effective point of suspension, the center of mass and the mass moment of inertia from the three equations of motion. If the damping moment at the joint is not negligible, it may be included in the problem as a viscous moment. The above procedure is then extended by the measurement of the decrement in the succeeding oscillations.

As a simpler but approximate procedure, a casting may be made of the segment (commonly used materials are plaster-of-paris and dental stone) and made to swing about a fixed point. Since the weight of both the actual segment and the cast replica can be found, the measured period can be corrected on the basis of the weights to represent the desired parameters of the actual segment.

In order to find the center of mass of the whole body, one of three devices may be employed. They are (1) first class lever, (2) second class lever, (3) force plates.

First class lever. The use of the first class lever is by far the most cumbersome procedure and is usually not recommended. It consists merely of a flat board on which the subject lies or stands and which is balanced over a single knife edge support. The other two methods are based on the fact that, if the forces on the supports of a given loading system are known, the line of action of the resultant load can be determined.

Second class lever. This method was first suggested by DuBois-Raymond (1900) and then used by Lowett and Reynolds (1910) and Basler (1931). In order to determine the X and Y coordinates (in a horizontal plane) of the whole body mass center, the subject is placed erect on a board supported by a weighing scale at one end as shown in Fig. 6. Knowing the weight of the subject and the distance between supports, the scale reading allows the line of



WHOLE BODY
MASS CENTER DETERMINATION

Fig. 6.

action of the subject's weight, hence his center of mass, to be determined.

To find the Z coordinate of the center of mass, the subject is placed supine on the board and the scale reading is taken. The principle of moments then gives the coordinate of the center of mass of the system. Since the weight and mass center of the supporting structures are known, the subject's mass center can be found by resolution of the loading forces.

Force plates. This method has been used by the New York University Prosthetic Devices Studies since 1950 [Contini(1954)]. The physical principle in this technique is identical with that of the second class lever. The difference is in the measurement of the reaction forces. In this case, a device called a force plate is installed to support the load and at the same time measure the value of the force on it. Since the entire load is supported by these plates, the subject's total weight and center of mass are determined at the same time.

The force plate consists basically of a flat aluminum rectangle, 15 × 20 in. supported at four corners by hollow aluminum columns. The loads on the columns are obtained through strain gages which are connected to form electrical bridges. The outputs of these bridges

are measured and recorded electronically to obtain the force on the plate. Simultaneously, another system of bridges records the X and Y coordinates of the mass center. A thorough discussion of the operation of the force plate can be found in Contini, Rishman, Drillis and Kransdorf (1953).

Determination of Moment of Inertia

Present studies on the moments of inertia of body segments involve two basic methods; one is based on the kinetic theory, Newton's law for rotation while the other is based on the oscillating pendulum idea.

Quick release method. Newton's law states that the torque acting on a body is proportional to its angular acceleration, the proportionality constant being the mass moment of inertia. Thus if the body segment, say the arm, can be made to move at a known acceleration by a torque which can be evaluated by applying a known force at a given distance, its moment of inertia could be determined. Such a procedure is the basis for the so-called "quick release" method. To determine the mass moment of inertia of a body segment, the limb is placed so that its proximal joint does not move. At a known distance from the proximal joint at the distal end of the limb, a band with an attached cord or cable is fixed. The subject pulls the cord against a restraint of known force such as a spring whose force can be found by measuring its deflection. The activating torque about the proximal joint is thus proportional to the force and the distance between the joint and the band (moment arm). The acceleration of the limb is produced by sharply cutting the cord or cable. This instantaneous acceleration may be measured by optical or electrical means and the mass moment of inertia about the proximal joint determined. This technique is illustrated by Drillis (1959).

Compound pendulum method. To determine body segment mass moments of inertia using the compound pendulum technique, refer to the previous section on center of mass evaluation.

A procedure for whole body moment of inertia studies using the theory of the compound pendulum has been developed by DuBois and Santschi (1962). In this technique, a pendulum is constructed so that it may accommodate an entire subject with sufficient restraint so as to oscillate as a whole. The double-axis system is employed, that is, the pendulum is oscillated about two different axes through the pendulum. Hence, four equations of motion are arrived at, for

- (1) pendulum and subject at short suspension
- (2) pendulum and subject at long suspension
- (3) pendulum only at short suspension
- (4) pendulum only at long suspension.

The equations may be solved for the subject's center of mass and moment of inertia by oscillating about each fulcrum and finding the associated periods.

DuBois and Sansfchi exhaustively discussed the errors involved, both physical and biological. In addition, a solution is given for large angular displacements of the pendulum: when $\sin \theta$ ceases to be approximated by θ . However, the use of these equations requires that the fulcrum frictional moment be small and that the subject is fixed to the pendulum in such a way that the two fulcrum points, the pendulum center of mass and the subject's center of mass lie practically on one straight line.

Torsional pendulum method. The torsional pendulum may be used to obtain moments of inertia of body segments and of the entire body. The pendulum is merely a platform upon which the subject is placed. Together, they oscillate about a vertical axis. The platform is restrained by either a coiled spring or a torsion bar fastened to the platform at one end and to the ground at the other. Knowing the physical constants of the pendulum, i.e., of the supporting platform and of the spring or torsion bar, the measurement of the period gives the mass moment of inertia of the whole body. To find this parameter with respect to different body axes, the subject need only change his position, say lying supine as opposed to standing erect,

to give the mass moment of inertia with respect to the two perpendicular axes.

This method can also be used to find mass moments of inertia of body segments. Nubar (1962) describes the necessary procedure and equations. Basically, it entails holding the rest of the body in the same position while oscillating the system for two different configurations of the segment in question. Knowing the location of the segment in each of these positions together with the periods of oscillation of the pendulum, the segment moment of inertia with respect to the medio-lateral centroidal axis may be found.

In addition, either the segment mass or the segment center of mass may also be considered unknown (the other being known) and evaluated by considering a third configuration of the segment with a third period of oscillation.

Since both the compound pendulum and the torsional pendulum methods may be used to find segment moments of inertia, the choice of one over the other is usually dictated by the segment involved. While the torsional pendulum has wider application, it is also the more intricate method as regards equipment required.

OUTLOOK FOR THE FUTURE

It is felt that the procedures outlined above will provide suitable results for body segment parameter determination of the living. The techniques can be used on a large population sample and nomographic charts developed so that the parameters may be easily found by obtaining the subject's anthropometric measurements.

Once found, the body parameters will contribute to improving the motor efficiency of the living and making his environment more comfortable. In the field of prosthetics, artificial arms and legs could be fabricated that are equivalent in function to the limb the amputee would otherwise possess. The volumetric studies discussed previously have significant application in the field of pathology. A disease

could be studied by observing the growth and/or shrinkage of the external body parts, measurements of which can be accurately determined.

With the growing interest in travel, both interplanetary and terrestrial, a knowledge of body segment parameters is requisite for the design of the necessary equipment. The data will enable more comfortable gear and seats to be designed and gages, pedals and such to be made more accessible.

In many areas there is a need for simulation of the human organism, be it a test dummy for auto-crash studies on seat belts, robots for moon exploration, or the like. In this work, there must be complete body parameter data.

The uses of body segment parameter data are quite numerous indeed. The complete evaluation of these quantities will be a significant contribution to biomechanics.

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