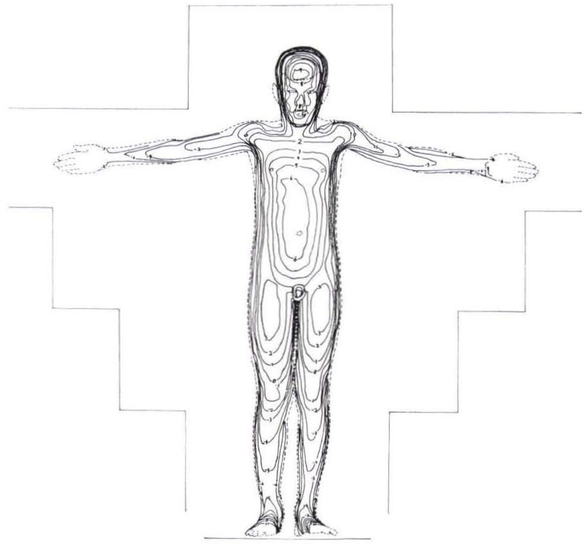
PROF. SIMHA WEISSMAN*
*University of Illinois*
*Urbana, Ill. 61801*



FRONTISPIECE. Front view map of the human body.

# Anthropometric Photogrammetry

## A most promising method for the determination of body volume, surface area, and shape.

### INTRODUCTION AND SURVEY OF METHODS

MEASUREMENT OF THE SIZE and shape of the human body is used extensively in such fields as anthropology, physiology, medicine and psychology. In spite of the long-standing interest in such measurements, universal agreement on the methodology of body measurements is still lacking. Two measurements in particular—body surface area and body volume—are generally considered as the most difficult measurements in human anthropometry. Over the years various methods have been established to measure body surface area and body volume. These methods may be grouped as follows:

*Coating Methods*. such as pasting small square pieces of paper over the subject and then measuring their total area, or using strips of millimeter paper wound around the body like a bandage. Clothing the body in tights, the area of which could be determined by weighing or by using a planimeter, is another possibility.

*Geometrical Methods*, such as dividing the body into parts which approximate geometrical figures (cones, cylinders) whose surfaces are given by simple and known formulas, and which require relatively few measurements of the body.

*Surface Integration Methods*, such as a cylinder of known area being passed over the whole surface of the body and the number of revolutions multiplied by the area of the cylinder yield the total area measured.

*Electronic Methods*, based on specially built instruments equipped with skin-touching rods or a charged metal plates of known area.

*Empirical Formulae*, yielding an estimate of the surface area. Such is, for example, Boyd formula (1935)

$$A_{cm^2} = 3.207\, W_{gm}^{0.7285-0.0188 \log W},$$

or DuBois formula (1916)

$$A_{cm^2} = W_{kg}^{0.425} \cdot H_{cm}^{0.725} \cdot 71.84,$$

where $A$ is the surface area, $W_{gm}$ is the weight

* Part of a research project conducted by the Dept. of Civil Engineering of the University of Illinois under the sponsorship of the Illinois State Dept. of Mental Health and the National Institute of Mental Health (Research Grant MH-NB-07346-01A1). (Figure 2 is reproduced with permission of *Life* magazine, published April 13, 1968.)

of the subject in grams, $H_{cm}$ is the height of the subject in centimeters, and $W_{kg}$ is the weight of the subject in kilograms.

The direct methods aiming at the determination of body volume utilize mainly:

1. Underwater weighing
2. Direct water displacement measurements
3. Gas dilusion* (rather than water displacement) measurements.

The methods mentioned above require a direct measurement of the body or physical involvement of the body in the process of surface area and volume determination.

ABSTRACT: *An investigation was initiated at the University of Illinois to design and implement a stereophotogrammetric data acquisition system for use in anthropometric studies. The system calls for a simple pose and minimal subject cooperation, and hence is universal in application. A special reference plane serves as a plane of orientation as well as a link in the formation of a round, mathematical or graphical representation of the subject. Experiments involving body surface area and body volume determination have been conducted, revealing the high potential of the photogrammetric approach.*

*The monophotogrammetric methods*, in contrast, call for the photography of the subject at a certain pose and the indirect measurement of the subject from the photographs or their projections. In most cases the subject stands on a turn table which is oriented for each exposure without having the subject change his position, thus obtaining a view of each side. Other methods are utilizing a specially built photometric camera which produces four images from a single exposure with the aid of mirrors. The surface area and volume can be obtained by approximating various portions of the body to known geometrical figures, or by assuming the shape of the horizontal cross section through the body to be an ellipse. The perimeter of such an ellipse can be computed from axes measured on the photograph, and the surface area between these ellipses is found by multipying it by the distance to the adjacent cross section. Still other methods are based upon utilizing projected colored strips of known width, or of a grid, on the photographed subject, thus reproducing the *contours* of the body at each level of depth.

The STEREOPHOTOGRAMMETRIC METHODS can be subdivided into two groups: *analog* and *analytical* according to how the photographs are used. In the analog methods the photographs are used as a basis for plotting a contour map from which measurements can be extracted, whereas in the analytical methods, coordinates measured on the photographs themselves are recorded. The surface area and volume can then be computed from these data following a scheme described later on.

It is evident that the stereophotogrammetric approach is the most promising means of body measurements. An investigation was initiated at the University of Illinois to design and implement a stereophotogrammetric data acquisition system for use in anthropometric studies. The intent of this investigation was to develop and examine a process of body measurement based upon the following criteria:

1. The method should be passive and efficient in the acquisition of the relevant data.
2. The method should yield reliable and complete information within reasonable limits of expense.
3. The method should require only a simple pose and minimal subject cooperation.

PROF. SIMHA WEISSMAN

* The subject is placed in a closed air chamber and helium is contained in a second chamber, both of known volumes and at atmospheric pressure. After mixing the gases, the concentration of helium is uniquely related to the volume of the subject.

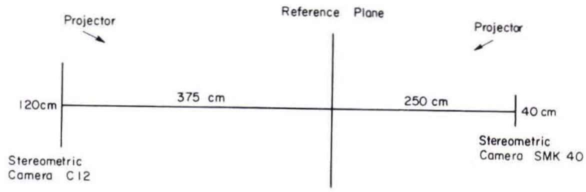



FIG. 1. Plan view showing the arrangement of the various parts of the photographic system.

The last criterion emphasizes the universality of the suggested method, enabling its extension to anthropometric measurements of children, mentally retarded patients, elderly people and the like.

## THE LAYOUT

The layout (Figure 1) is designed in such a way as to enable a quick taking of photographs without altering the position or attitude of the cameras or the subject's pose during the process.

A reference plane, made of 3/4-inch plywood sandwiched between a double frame, was designed and set perpendicular to the floor. The subject stands on a stool so that the reference plane bisects the subject's body transversely, i.e., half of his body is protruded from the reference plane to the front and to the rear. The cross-like configuration at three different levels cuts off the reference plane, and accommodates for the outstretched arms of individuals of different height (Figure 2). At each side of the reference plane three points were marked as control points. The distances between the control points were measured to serve for scaling purposes. The *height* (actually the orthogonal distance to the camera) of these points was considered to be zero.

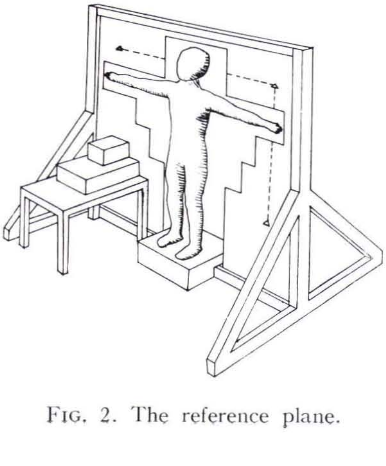


FIG. 2. The reference plane.

The cameras to be used in such a work must be synchronized, have a long focal length, large negative area, be able to focus on near subjects, and remain stable during long operation periods. The cameras available for this investigation were the WILD C-12 and the Zeiss SMK-40 stereometric cameras, consisting of two synchronized chambers rigidly mounted to a base of a precisely known length (120 cm. and 40 cm. respectively). The cameras were placed in front of and behind the subject. The subject, standing between the two cameras, was photographed simultaneously, thus eliminating the need for a turntable. In this way the total photographic process was shortened and the demands on the subject were lessened. The only possible disadvantage is the fact that some areas along the sides of the subject were not recorded. We shall show later that the loss is not too great. However, should the need arise for a complete coverage, a rotation of the subject over an angle of 90° with two additional sets of simultaneous stereophotographs of the sides will still be the most efficient method as far as time and cooperation of the subject are concerned.

There is no need for illumination in addition to the regular room light, provided that a highly sensitive emulsion is used such as Kodak Super Orthopress (ASA 250). By avoiding the additional illumination, the layout becomes less expensive and less elaborate, and more importantly, it becomes possible to project a grid on the subject and photograph it clearly. The projected grid replaces the traditional premarking of the subject in countering the problem of observing and measuring the uniform texture of the human skin.

The unique feature of the arrangement is the way the reference plane is used as a plane of orientation as well as a link between the rear and front views, forming one round mathematical or graphical figure.

In order to study the practicability of the system in reducing the active cooperation of the subject to a minimum, seven mentally retarded children were instructed to stand on

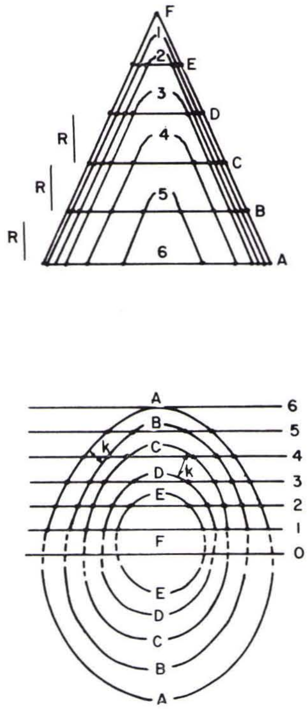



FIG. 3. The upper diagram (Figure 3a) is a conical structure drawn in the $XZ$-plane. The lower diagram (Figure 3b) is the projection of the conical structure onto the $XY$-plane.

the stool and stretch their arms sideways, and this was accomplished without difficulty. No marking or adhesive materials were put on their naked bodies and no measurements of any kind were taken directly off them except their weight. The seven subjects were photographed and weighed within 20 minutes which included time for unloading and reloading the cameras after each exposure.

## Data Acquisition and Reduction

The WILD A-9 Autograph was available for the work at hand. The rather limited range of possible model and map scales, as well as the need for a vertical scale different from the planimetric one (due to the impossibility of the instrument to accomodate for the short focal length of the camera), does not make it the most suitable instrument for such a purpose. However, it should be emphasized that for overall accuracy, efficiency and convenience, this instrument is superior to instruments like the Kelsh plotter, often used for similar projects.

The operational procedure is as follows:

1. The reference plane, being a physical one, serves as the plane on which the relative orientation can easily be made.
2. Scaling of the model is done by using the known distances between three points marked on the reference plane.
3. Leveling of the model is done by bringing the reference plane to an absolutely horizontal position, i.e., the elevation of the reference plane everywhere is zero.
4. The zero contour line (reference plane elevation in the front-view model) was plotted wherever observed on the body. The other contours thereof are marked 1, 2, 3, etc., denoting the actual vertical interval of 1 cm. between them. A contour line lower than 0 was indicated by a minus sign.
5. The elevation of the reference plane on the back view model must take into account the tickness of the plane. In this case, its elevation is +1.8 cm. Thus the reference plane becomes truly identical for both the front and the back views. The contour lines on the back view map will also be marked 0, 1, 2 ,etc. It is obvious now that the −1 contour line of the back view map is identical with the +1 contour line of the front view map and vice versa. In the same way contour +3 of the back view differs 6 cm. from the +3 contour of the front view.
6. The boundaries of the stereoscopically viewed body, as well as any other *planimetric* detail such as the nipples and navel, should be plotted. The cross-like outlines of the refernece plane is also a part of the map. The resulting map (Front View) is represented in the Frontispiece.

## Data Processing

Surface area can be computed from measurements taken either from a plotted map or directly from a plotter. If the map is drawn on the $XY$-plane and contains sufficiently dense contour lines (vertical interval = 1 cm. or less) which represent horizontal section through the body, then denoting:

$R$ = the vertical interval between two successive horizontal sections $i$ and $i+1$,
K = the horizontal interval on the map averaged from several measurements at different locations,
$S$ = scale number of the map, and
$E_i$ = circumference of section $i$,

the surface area between two such sections can be computed by the following formula:

$$A = \frac{E_i + E_{i+1}}{2} \cdot \sqrt{(R.S)^2 + K^2}.$$

Such a map can be obtained either by using instruments capable of interchanging the $Z$ and $Y$ axes (like the WILD A-7) or by graphically converting maps drawn on the $XZ$-plane into maps drawn on the $XY$-plane before measuring the various parameters. In order to demonstrate the later possibility, a conical structure (Figure 3a) drawn in the

$XZ$-plane has been converted into its corresponding figure in the $XY$-plane (Figure 3b). The last figure contains both the front and back views of the structure to form a round figure. The unphotographed areas, and therefore missing portions along the sides, can easily be interpolated (dashed lines in Figure 3b) without deteriorating significantly the overall accuracy. The method shall be referred to as Method 1.

The Graphical conversion of the map, although requiring an additional step, enables the use of less expensive photogrammetric plotters. Moreover, the parts of the body resembling a cylindrical shape need not be graphically converted from the $XZ$-plane into the $XY$-plane and hence the amount of additional work is reduced. Dividing the cylinder into longitudinal sections containing contour lines with equal horizontal intervals, and denoting:

$B$ = the width of each section, averaged from top and bottom measurement,
$C$ = the number of 1-cm. contour intervals contained in the section,
$h$ = the length of the section i.e., the height of the cylinder, and
$s$ = the scale number of the map,

the area of each such section is:

$$A = \sqrt{(B \cdot S)^2 + C^2} \times h \cdot s.$$

For the unplotted sides of the cylinder, $C$ is the gap between the last plotted contour on the front view and the first plotted contour on the rear view map. Because at these places $B = 0$, the surface area of the side section is:

$$A = C \cdot h \cdot s$$

The sum of the areas of all sections is the surface area of the cylinder. The result should be smaller than the actual area because it is a combination of planar areas rather than curved ones; yet with a contour interval of 1 cm. the difference is negligible. We shall refer to this method as Method II.

The volume can be computed as follows:

$$V = \frac{G_i + G_{i+1}}{2} \cdot h$$

where $G_i$ is the planimetric area of horizontal section $i$ (measured with a planimeter or a similar device) and $h$ is the vertical distance between sections $i$ and $i+1$ (measured off the map). The sum of all these volumes is the total volume of the body.

Using measured coordinates as the sole input data is another possible approach to surface area and volume determinations. The coordinates can be measured:

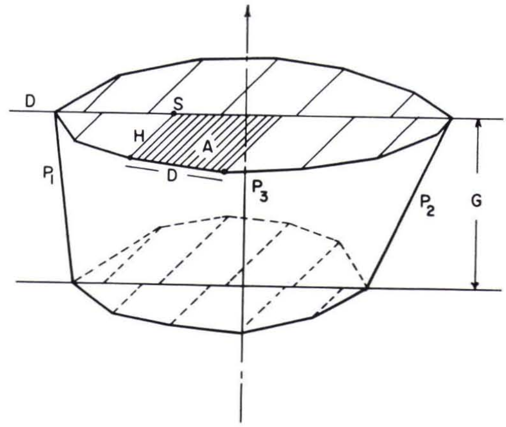



FIG. 4. The various parameters involved in the computer program.

1. Off a contour map
2. Off the optical model in the analog type instrument
3. Off the photographs themselves (by means of a stereocomparator)

Possibilities 1 and 2 are geometrically identical and hence will be regarded as one and denoted as a *semi-analytical method*, whereas the third possibility will be denoted as the *purely analytical method*. Inasmuch as a graphical representation and visual tests are often very important in works like the one at hand, the semi-analytical method seems, in this particular case, to be more convenient than the purely analytical method. Machine coordinates are measured and recorded along selected horizontal sections of the body. The data so collected is far more accurate than that collected from map measurements. It is preferable to use an automatic readout capable of punching the coordinates on IBM cards which then become a part of a program whose output contains the circumference of the horizontal sections, their area, the surface area between any two of them, the total surface area of the body and its volume.

The program itself is written according to the following principles: The slant distance between any two points ($D$ in Figure 4) whose coordinates were measured along the same horizontal section, is computed. The sum of all these distances is the circumference of the section. The area bounded by the slant distance, the zero reference line ($X$-axis), and the two ordinates of the corresponding two points ($A$ in Figure 5), is easily computed and the sum of all these areas is the area of the section. The average area of two adjacent

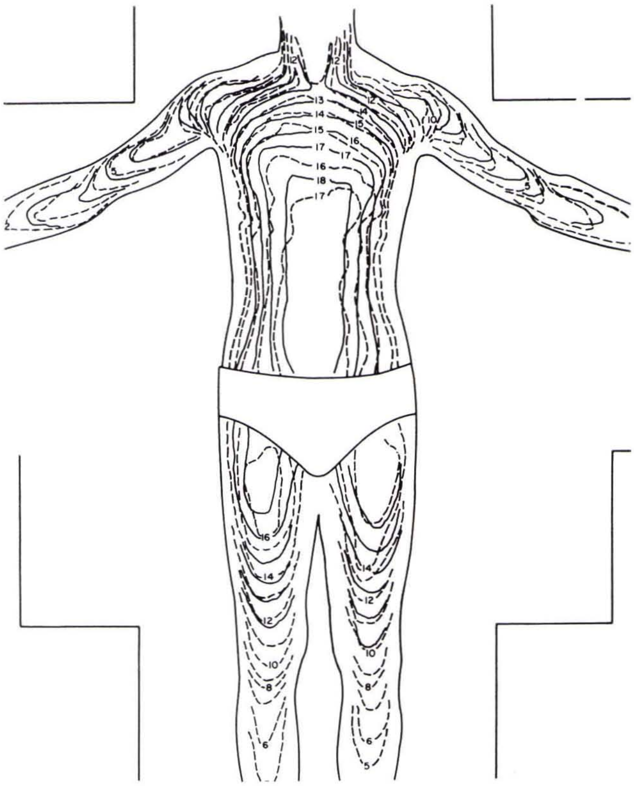


FIG. 5. The effect of respiratory changes on the contour lines.

sections multiplied by the vertical distance between them will yield the volume of that portion. The average circumference of two adjacent sections multiplied by the average slant distance between the sections yields the surface area of this portion. The average slant distance between the two sections is computed from measurements at three locations: center and each end ($P_1$, $P_2$, $P_3$ in Figure 4).

Actually, the program gives the surface area, volume, circumferences, and areas of sections for the back of the zero reference plane and for the front part separately, and the addition of any corresponding dimensions is the final result. We shall refer to this method as Method III.

## EXPERIMENTS AND RESULTS

Geometrical objects of known surface area and volume as well as live subjects were photographed and analyzed. It was found that the accuracy of surface area determinations were very high for all Methods I and II and III; the discrepancy in all instances was less than 1 percent. It should be emphasized that the more irregular the figure, the less reliable and convenient is Method II for measuring the surface area. Method II can, however, be applied successfully to circular or cylindrically-shaped figures.

A further comparison between Methods I and III indicate that the results obtained by the semi-analytical method were not better than those obtained graphically probably because the program in its present stage does not compute best-fitting curves between the measured points.

As far as the accuracy of volume determinations is concerned, the results are not too different from those obtained in the case of surface area. Here, Method I gives results which are closer to the *actual* values than does Method II, but both figures differ from the actual value by less than 1 percent.

Circumference measurements are an integral part of both volume and surface area determinations; they also are of anthropometric interest in themselves. Unlike volume and surface area, the *actual* values of the circumferences can be measured not only on still objects but also on the living. Of course, the assumption made here is that the direct measurement of a circumference *is* its actual value. This assumption is a very rough one, especially in view of the fact that in the methods suggested in this paper, no instruction is given as to how and when the subject should breathe as he is being photographed.

The circumferences of the sections through the nipples and the navel as obtained by means of the analog method deviated 0.6 percent and 0.5 percent, respectively, from their directly measured *actual* values. Along the same circumferences, the machine coordinates of several points were recorded and plotted. Best-fitting curves were plotted through these points and their lengths measured. Comparing these results with the actual values, the deviations were 0.2 percent and 0.1 percent, respectively. The same circumferences obtained by analytical computations, without resorting to graphical plotting or curve fitting, yielded a difference of 0.7 percent and 1.0 percent as compared to the directly measured values.

It was pointed out previously that no instruction was given to the subject to alter his breathing pattern. In an attempt to answer the question as to what effect this might have had on the measurement, the subject was photographed twice, *mapped* twice, and then the two plots were superimposed (see Figure 5). The results showed a shift in the order of 1 to 1.5 cm. of the contour lines at the chest levels most affected by respiratory changes. Although no definite conclusions can be drawn from just one such experiment, this case suggests that the error due to *normal* respiratory changes is probably small.

Other experiments involved a check on the reliability and precision of the contour lines by plotting them twice, as well as by comparing them with direct spot elevation measurements.

The results of these and other tests conducted so far, lead to the conclusion that, of the currently available methods of body measurements, photogrammetry seems to be the most promising on account of its accuracy, efficiency, versatility, and ease of record keeping.

It is logical to expect that the accuracy of the photogrammetric procedure would be greatly enhanced by the use of larger-scale metrical photography and universal stereoplotting instruments.

## References


1. Blesh, T. E. Postural analysis of Yale University freshmen. PHOTOGRAMMETRIC ENGINEERING, 1956, 22, 357–366.
2. DuBois, D. & DuBois, E. F. A height-weight formula to estimate the surface area of man. *Proc. Soc. exp. Biol. Med.*, 1916, 13, 77–78.
3. Hertzberg, H. T. E., Dupertuis, C. W. & Emanuel, I. Stereophotogrammetry as an anthropometric tool. PHOTOGRAMMETRIC ENGINEERING, 1957, 23, 942–947.
4. Miskin, E. A. The application of photogrammetric techniques to medical problems. *Photogrammetr. Record*, 1956, 8, 92–111.
5. PIERSON, W. R. Photogrammetric determination of surface area. PHOTOGRAMMETRIC ENGINEERING, 1961, 27, 99–102.
6. Weissman, S., & Herron, R. E. Stereophotogrammetry as a means of Anthropometry for Mentally Handicapped Children. Civil Engineering Studies, *Photogrammetry Series No. 11*, University of Illinois, 1967.