THREE-DIMENSIONAL MEASURING METHODS:
A REVIEW OF THE TECHNOLOGY
AND THE DEVELOPMENT OF A METHOD
FOR MEASURING THE HUMAN BODY

by

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(ABSTRACT)

The type of measurements that can be used to describe the body are dependent upon the measuring instruments used. Traditionally, the body has been measured with a tape measure, calipers and, an anthropometer. These instruments, however, provide only two-dimensional measurements. Two-dimensional measurements specify a magnitude of the body that is located within a single plane. Unless the relationship between these measurements can be specified, very little information is conveyed which describes a three-dimensional form.

Advances in technology have provided instruments and methods which provide precise three-dimensional measurements. These three-dimensional measuring systems were investigated as a means of measuring the human body.

The purpose of this study was to identify a means of defining and specifying an average three-dimensional human form from any given sample of human bodies. Existing measurement methods were first identified and analyzed for the feasibility of their use to complete this study. Because an economical and completely developed method which provided detailed and comprehensive information about the body was desired, the

development of a new method was undertaken.

The method which was developed did not provide accurate information. Further refinements of this method may yield better results in the future. However, it may be more advantageous to pursue the further development of an existing method of three-dimensional measurement.

DEDICATION

To Rollin,
for always being there.

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INTRODUCTION

Background of the Problem

Consumers and clothing professionals agree that purchasing ready-to-wear clothing which fits properly is a difficult and sometimes impossible task. Consumers consistently list the fit of clothing as a major source of dissatisfaction (Sieben, 1988). Even when consumers are moderately satisfied with the availability of clothing in their size range they are not satisfied with the search process required to find clothing which fits (LaBat, 1987). Career women rank the fit of clothing as one of the most important factors influencing their purchases (Hagan, 1988). The annual losses due to garment return because of poor fit in 1978 were estimated at $175 million for one retailer alone (Owings, Schneider, & Snyder, 1978). The problem of clothing which fits poorly is frustrating and expensive for consumers and retailers alike.

Clothing manufacturers have several alternatives in designing garments. A garment pattern may be designed by using a flat pattern method which utilizes either a sloper or drafting techniques, or by draping. Regardless of which method is used, at some point in the process the garment must be placed on a body or body substitute (manikin) in order to determine the correct fit. It is possible to use live fitter's models for this process, but at a cost of $120/hour (personal correspondence, Tatiana's Models & Fitters, 1989) it is not economically feasible to do all the necessary fitting in this way. At this rate a manikin can pay for itself with five hours of use. It is also not always possible to find a model with the exact measurements desired or one that will maintain those measurements for the entire time period of use. Therefore, it is most common for a workroom manikin to be used for fitting purposes. Manikins are also easier to use than a real body because they are marked with the reference lines required in garment design such as the center front and back lines, shoulder lines, waistlines, and princess lines and because pins can be inserted into their surfaces.

Problems occur, however, when the form which is used is inaccurate in the manner in which it replicates the human body. When the form conforms to the body's size and shape in only some respects the clothing which is fit upon it will require further alterations when placed on an actual body. Researchers in the clothing field are becoming increasingly aware of the link between clothing which has been fitted upon the manikin and problems in the fit of ready-to-wear.

Hutchinson and Munden (1978a) compared two British workroom manikins with live subjects and found differences, especially in the shoulder area. These differences were large enough to produce serious fitting problems. The shoulder area is of critical importance in fitting a garment. Most garments, however loosely they fit the body, are suspended from the shoulders. "If a clothier could rely on being able to produce garments which fitted the figure perfectly between the neck and a horizontal line encircling the figure at depth of scye height, his main difficulties regarding fit would be overcome" (Hutchinson and Munden, 1978a, p. 70). The fact that this particular area of the manikin is incorrect in its representation of the human body is cause for concern.

Heisey, Brown and Johnson's (1988) research on three-dimensional pattern drafting refers to the problems in fit which can occur by using a form "...that is correct in its major circumferences and lengths but not in the precise spatial relationship between circumferences" (p. 5). A Clothing and Textiles professor at Virginia Polytechnic Institute and State University experienced this very problem while working with a major catalog company. Manikins that were ordered to duplicate the company's fitting models were accurate in the girth and length measurements but incorrect in the location and shape of contours. The position of the shoulders was also inaccurate (J. Boles, personal communication, January, 1988).

There are only a few companies that produce the type of manikin used by the garment industry. Of these, only two are major suppliers to the industry. Both have been in business since the beginning of the century. When commenting about their forms one manufacturer assures us that "the same technique is used today as when they were first made at the turn of the century" (Montalto, personal correspondence, May, 1988). The catalog produced by the other claims that "Your every measurement and contour will be incorporated in an exact replica of your form" (Wolfe, no date available).

It is interesting to note that even though the dimensions of the manikins do change over the years (see Table 1 for dimensions of size 10 manikins from 1954 to 1988) these changes are not a reflection of actual changes in the body shape of the population but instead are due to changes in fashion. Fashion follows social changes and reflects the

Table 1.

Measurements of Size 10 Wolfe forms

Year	Bust	Waist	9" Hips	Front Length	Back Length
1954	35	25-1/4	34-1/2	13-7/8	16-1/8
1960	34-1/8	24-3/4	34-1/2	13-7/8	15-3/4
1972	35-3/8	24-3/4	36	14-1/8	16-1/8
1976	34-1/4	25-1/8	36	14-1/8	16-1/4
1988	35-5/8	26-1/8	36-3/4	14-1/2	17

Note. Measurements are in inches.

dominant ideals of a culture (Horn & Gurel, 1981). Some fashions require a re-molding of the body which is usually accomplished with some type of undergarment. As fashion allowed girdles to become less common and bras less restrictive the manikin was remolded accordingly. When waists are designed smaller or shoulders broader the manikins are changed to accommodate the trend. The tight bodices that the influential St. Laurent brought back in the late 1970s demanded the production of a new manikin by a British "stand" manufacturer (Rhodes, 1977). Fashion designers interpret the current cultural ideals which in turn dictate the "ideal" body for women who are to wear the current styles. It is then left up to women to conform to this ideal.

This focus on the ideal figure instead of the real figure has had negative effects on women. As well as influencing the fashion and fit of their clothing it leads them to believe that it is not the clothing that does not fit their bodies but their bodies that do not fit the clothing. They have come to believe that they are the problem. As the ideal body changes over time, so does a woman's image of her own body. During the 1950's this self-image was best paraphrased by Jourard and Secord (1955), "It is good to be smaller than you are in all dimensions except bust" (p. 246). The current concept of the ideal body is reflected in the results of a 1988 Gallup Organization poll. The poll reported that the current American woman wants to be taller, weigh less and wear a size 8. Forty percent also want a more muscular body (American Health Magazine, 1988).

The body is most often described in terms of its two-dimensional qualities. Anthropometric measurements and garment specifications are written using two-dimensional information.

Attempts made to more completely specify the form of the body have usually only been to increase the number of two-dimensional measurements taken on each body. Even a large number of two-dimensional measures requires considerable interpolation to actually reconstruct the three-dimensional form of a body. Specifying the relationship between two-dimensional data is necessary in order to convey information about a three-dimensional form.

The body is a three-dimensional form. It would appear that the major problem with the present workroom manikin is the result of a failure to consider the relationships between various two-dimensional measurements of the body. A method of measuring the body in all three dimensions is necessary. This research will attempt to identify a means of measuring the body with three-dimensional information which will give not only the usual anthropometric data but also the relationships between these two-dimensional measurements.

The task of fitting a population of women with greatly varying bodies is not an easy one. The inaccuracies of the workroom manikin make this task even more difficult when the manikin is used as a fitting device. In the Apparel Research and Development Laboratory (R & D Lab) of Virginia Tech efforts are underway to solve part of this problem by re-designing the workroom manikin so that it is a better representation of the human body. The current research is a part of a larger research project (manikin project) conducted by the R & D Lab. The focus of this initial project will be on identifying a method to describe the dimensions and contours of a female body in three dimensions. This method will then be used with a large sample of women of a particular size range so that information can be gathered from which a representative manikin can be constructed. Later implementation of this research may use samples comprised of different sizes as well as with either sex and varying age groups.

After a method has been established to specify the three-dimensional size, shape and form of each particular body in the sample, a means of analysis will be determined to quantitatively compare specific areas of the body of all members of the sample in order to determine the specifications of the average body contours of the sample group.

Statement of the Problem

The purpose of this research is to identify a means of defining and specifying an average three-dimensional human form from any given sample of human bodies.

The Subproblems

1. The first subproblem is to identify existing methods of three-dimensional measurement.

2. The second subproblem is to determine the criteria which govern the solution to this problem.

3. The third subproblem is to develop and pre-test a three-dimensional measuring method based on the established criteria.

Assumptions

The assumption made in this study is that the availability of a three-dimensional measuring method would provide the means of establishing a data base to describe a given population with more comprehensive information. This information could be used by the garment industry, manufacturers of workroom manikins, and others in order to provide improved sizing for clothing.

Operational Definitions

workroom manikin - a three dimensional form manufactured in different sizes to represent the human body, used for fitting garments. Most workroom manikins are made on a metal frame covered by a padded material with a canvas-like cover. Forms extend from the neck to either mid-thigh or with full length bifurcated legs; forms are truncated at the armscye line although separate arms may be attached.

size - the spatial magnitude of a body measured either as a circumference or as the distance between two points.

shape - the flat boundary of an object identified in two dimensions, usually length and width and contained in one plane. In the Cartesian Coordinate system this would be represented by x and y coordinates.

form - the boundary of an object identified in three dimensions, usually length, width and depth which encompasses at least two planes. In the Cartesian Coordinate system this would be represented by x, y and, z coordinates.

anthropometric measurements - measurements taken on the human body with a caliper, anthropometer, or tape measure from an identifiable landmark or endpoint to another or taken circumferentially.

body landmarks - specific anatomical points located on the body which are based on the boney projections of the underlying skeleton.

sagittal plane - the imaginary plane passing vertically through the body dividing it into right and left halves. The anteroposterior median plane of the body or a plane parallel to the median.

anthropometer - a measuring device with horizontal arms which stands on the floor and measures vertical distances of the body.

2-D measures - measurements taken in only one plane including lengths, widths and, girths.

3-D measures - measurements that may be made between points which have been located on two planes and specified by x, y and, z coordinates.

average body - the body representing the composite of mathematical means of body measurements of the sample for each area of the body which is analyzed.

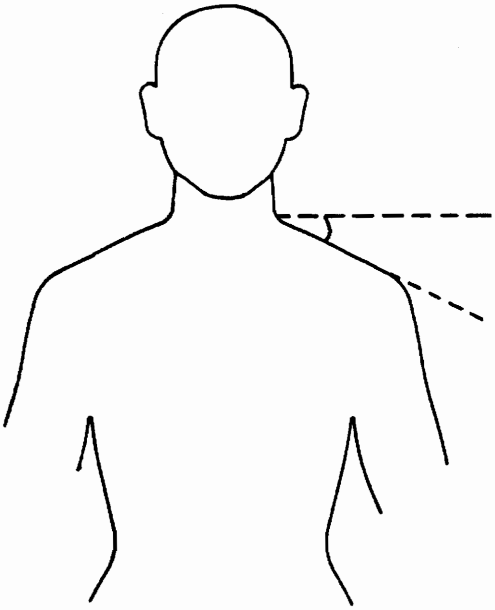
diffuse object - an object (such as the human body) which does not have easily identifiable edges or sides.

REVIEW OF LITERATURE

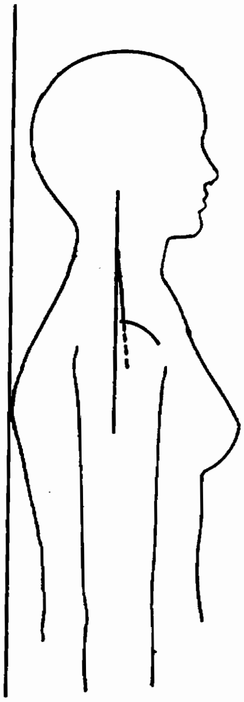
The majority of ready-to-wear manufacturers use workroom manikins when designing and inspecting garments (Hutchinson & Munden, 1978a, Boles, personal correspondence, January, 1988). The continued use of these forms for pattern-making and garment inspection makes it imperative that the workroom manikin be a close representation of the human body. Each manikin must reflect the dimensions, contours, and posture that are most representative of a group which is defined by a particular size range. Ideally, new standardized sizes should then be adopted which reflect these actual contours and dimensions.

Hutchinson & Munden (1978a) conducted a study of the size, shape, and stance of 44 women using three-dimensional measurements and compared the data to that of two workroom manikins. They divided the women in their sample into three age groups for analysis. Their study showed some significant differences between the shapes of the manikins and that of the women.

Special adjustable protractors were used to measure the angle of shoulder depression and the forward angle of the shoulder (see Figure 1, a & b). The angle of shoulder depression or shoulder slope (the angle that the line along the shoulder makes with the horizontal) of the manikin was found to be inaccurate when compared to the shoulder slope of the sample. The Hutchinson & Munden survey found that this angle measured between 19-25 degrees for all subjects (n = 44). One of the manikins measured was approximately equal to this average (angle = 21°). The other manikin, however, had a shoulder slope of 24 degrees. This angle was greater than all but three of the subjects measured and was 3



a) Angle of shoulder depression
(shoulder angle)



b) Forward angle of shoulder

Figure 1. Angles measured in Hutchinson & Munden survey

Note. From "The geometrical requirements of patterns for women's garments to achieve satisfactory fit" Part I by R. Hutchinson and D.L. Munden, 1978a, Clothing Research Journal, 6.

degrees greater than the average of all subjects. Although the British Joint Clothing Council (cited in Hutchinson & Munden, 1978a) had previously conducted a large-scale survey (published in 1957) with a sample of 5,000 women which included this measurement, this information was not reflected in the shape of the manikins.

The forward angle of the shoulder of the manikin also was not representative of the Hutchinson & Munden sample. While the Hutchinson and Munden sample measured between 9-16 degrees this angle on the manikin measured only 2-4 degrees. The researchers concluded that these significant differences were enough to affect the fit of clothing for the average woman.

Measurements taken on the sample across the back in the horizontal plane indicated an increase in curvature with increasing age. Although one of the stands was similar in curvature to the younger groups the other stand was much flatter than any of the three age groups. Other differences were also noted such as the stands being greater in measurements of back width and length than the human subjects.

"Often consumers encounter fit difficulties in specific locations within garments" (Sieben, 1988, p. 50). When consistent fit problems are identified the question of whether the garment was fitted on a live model or a workroom manikin needs to be considered.

Analyzing the Human Body

Whole sciences have been built on analyzing specific aspects of the body due to its appearance, functions, or its interaction with the environment. Only those areas which relate to the surface of the body will be examined in this review. "...the human body seems to have an inordinate number of irregularly curved and angular depressions and projections, as well as an assortment of appendages, all of which tend to impede a straightforward design solution" (Annis, 1978).

The body can be analyzed either subjectively or objectively. Studies of the human body began as either objective two-dimensional analyses or subjective analyses. Measurements were taken on the body first by physically contacting the body (direct measurements) and then through the development of non-contact measurement systems (indirect measurements). These types of analyses became increasingly refined and led the way to objective three-dimensional analysis of the body form.

Contact Two-Dimensional Analysis

Anthropometric Studies

Most available data which objectively describe the human body are the result of anthropometric surveys. Traditional anthropometry involves gathering body measurements by directly observing and contacting the human body. Anthropometry is derived from the Greek "anthropos" (man) and "metrein" (to measure). Landmarks based on the boney projections of the underlying skeleton are usually marked on the body as repeatable reference points (see Figure 2). Primary dimensions, such as major girths, are then measured using these reference landmarks.

Traditionally, anthropometric studies have been done with a steel tape, an anthropometer, and calipers (see Figure 3). The steel tape is used to measure body circumferences, the anthropometer for all linear dimensions, both vertical and horizontal, and the calipers for spanning width and depth measurements.

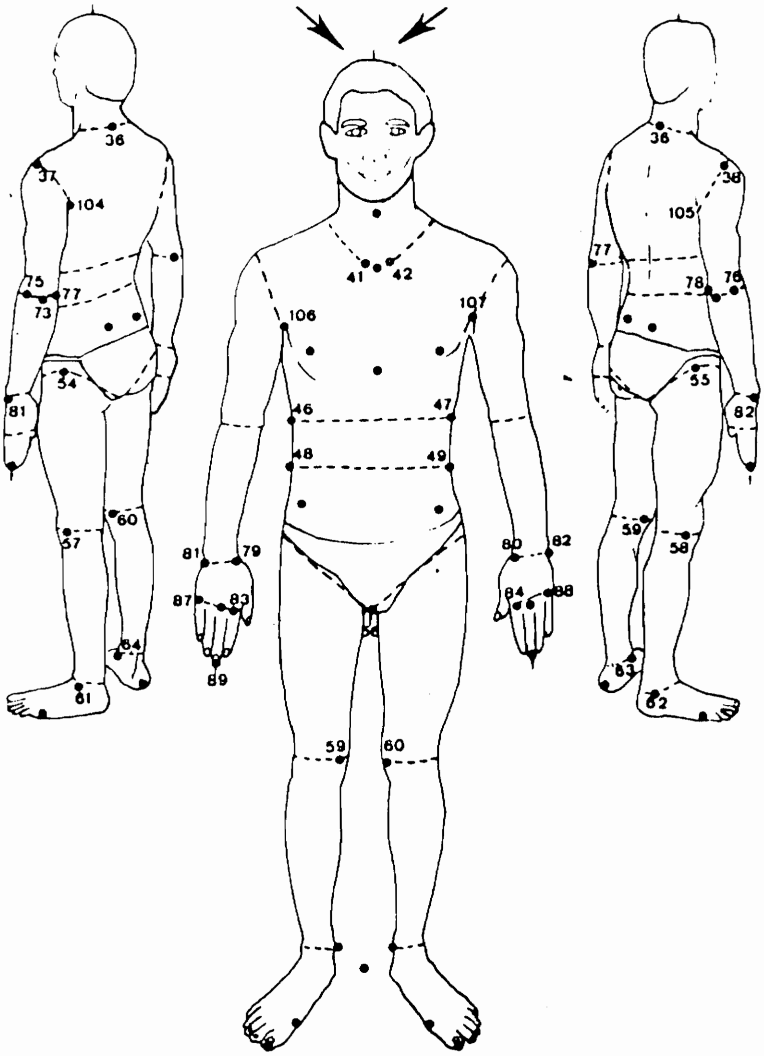


Figure 2. Location of commonly used anatomical landmarks

Note. From "Biostereometric study of a sample of 50 young adults" by R. Mollard, M. Sauvignon and, J.C. Pineau, 1982, Proceedings of SPIE-The International Society for Optical Engineering, 361, p. 236.

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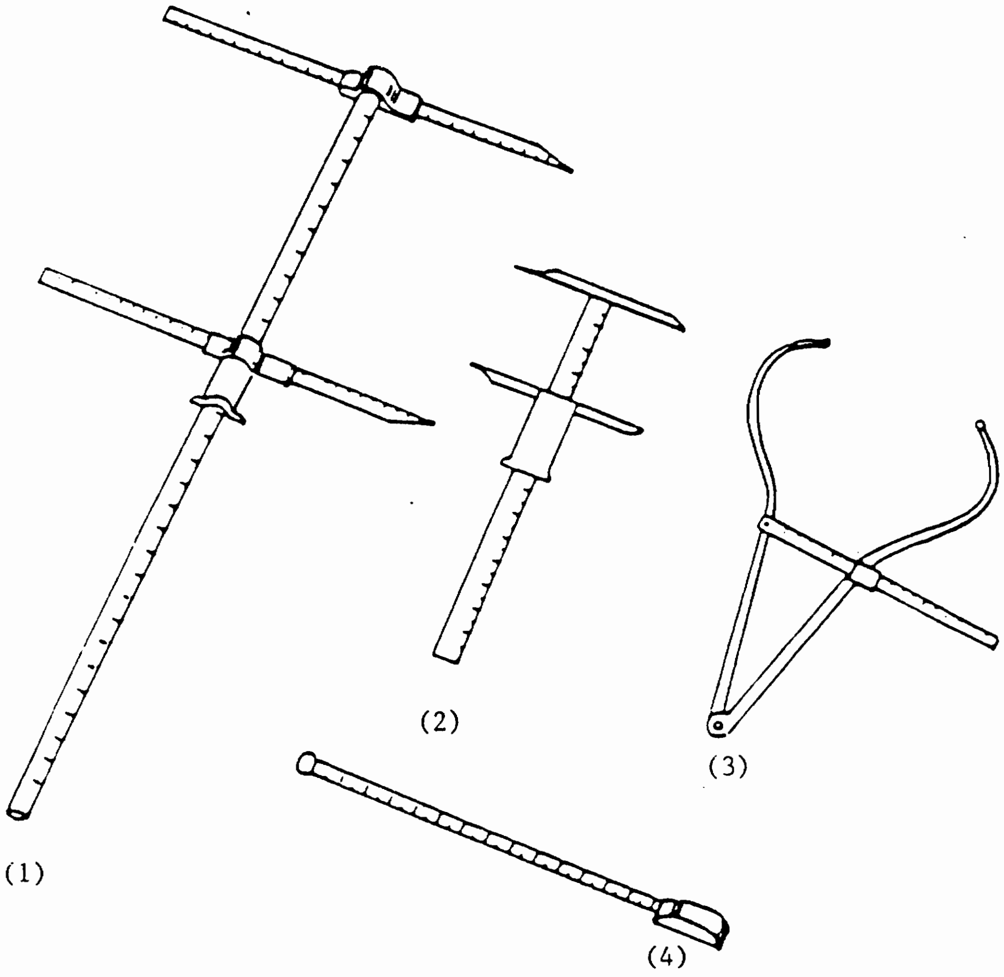

Figure 3. Classical anthropometric instruments

1. Anthropometer
2. Straight calipers
3. Spreading calipers
4. Tape

Note. From Engineering Physiology (p. 10) by K.H.E. Kroemer, H.J. Kroemer, K.E. Kroemer-Elbert, 1986, Amsterdam: Elsevier Press.

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Each anthropometric study is based on the needs of its user and seldom exactly duplicates another in the list of which dimensions are considered essential. The variables to be measured not only vary but most often grow in number. The 1942 Army Air Force study used 55 measurements; in the 1950 Air Force study the number had grown to 132 and in 1967 the number had reached 190 (McConville & Laubach, 1978).

Not only do the specific measurements taken vary from study to study but there are often subtle differences in techniques used regarding placement of landmarks and measuring practices. Even though the variation in measurement data produced by these differences may be so slight to be of little significance, it is best to have an awareness that such conditions exist (McConville & Laubach, 1978).

Many of the first large-scale anthropometric studies were conducted to satisfy the military's need for data in order to clothe and equip large numbers of men. The military is still the foremost source of anthropometric data for this same reason. The data base describing the military population is substantially larger than that of the civilian population.

As the ready-to-wear industry grew this same type of data became necessary to describe the civilian population. In response to this need, the United States Department of Agriculture undertook a large-scale comprehensive survey of American women in 1939. The results of this study, published in 1940, reflect 55 measurements taken on each person in a sample of 10,042 women. The data were analyzed to determine sizing ranges in an effort to improve garment and pattern fit. A manikin which represented each size range was set as a goal of the study

(O'Brien & Shelton, 1941). Results of the study revealed that no single measurement could be used as a basis for sizing. Both a vertical and horizontal measurement were necessary to reflect a woman's height and girth. The most highly correlated measurements in this study were height and weight. The study resulted in the compilation of a substantial data base representing Caucasian American women.

The National Aeronautics and Space Administration (NASA, 1978) has compiled a comprehensive collection of anthropometric studies, both military and civilian. The studies which are included in the NASA collection were conducted between 1939-1974. At least twenty focus solely on women with sample sizes ranging from 75-10,042 and ages ranging from 17-79. Data are included from every populated continent in the world.

During the 1950s there was a surge of activity among anthropologists. It was common for each anthropologist pursuing his/her own particular approach to the study of anthropometry to invent his/her own new measuring instrument. This array, however, has been reduced to a minimum for practical field work. Most large-scale studies have been conducted with the basics of a tape measure, an anthropometer, and a few calipers (Jurgens, 1980).

Advances in computer technology have led to automation in the process of collecting anthropometric data. An automated system developed at the University of Michigan has been used in two national anthropometric studies. The system provides electrical readout of anthopometric data. Pressure sensors are used in measuring soft tissue areas of the body. The data are fed into a computer system for storage.

The advantages of automating anthropometric measuring are significant. Measurement and recording errors are minimized or eliminated. Data describing the measurements of a population are easily stored, reduced, and analyzed (Snyder, 1980).

Non-Contact Two-Dimensional Analysis

Non-contact body analysis first became possible by the use of photography. Sheldon established a categorizing system of three body types based on the proportions of male bodies (Sheldon, Stevens, & Tucker, 1940). These categories, referred to as somatotypes, from the Greek soma (body), were originally based on intuitive assessment, although in later developments of Sheldon's system by others quantifiable measurements taken from the photographs were used.

The use of anthropometric photography as an acceptable research tool was the subject of many articles in the 1950s although it was not until the 1970s that it was commonly used. Early studies were of a subjective nature and, like Sheldon's work, described the general form of the body.

Further developments of Sheldon's work took two different forms. One group continued to view the body silhouette as it was captured in photographs. The other group attempted to standardize and perfect the use of photography as a tool for taking quantifiable anthropometric measurements.

Douty (1954) saw that a technique similar to Sheldon's would be an asset to her clothing class enabling her students to objectively view the shapes of their bodies. She further developed Sheldon's system by photographing the silhouettes of women subjects which were projected through a translucent gridded screen. The silhouette photographs served to protect the anonymity of the subjects involved and provided a simplified picture of each person's body contours. The "somatographs" were used for subjective analysis of posture, body mass, proportion, contour, balance, and symmetry.

Analyzing the body with somatographs became a fairly common research practice in the clothing field. Additional information about the body was available from the somatographs that could be used in the alteration of patterns. Angles and contours which are visible in silhouette photographs were measured by researchers seeking to develop non-traditional pattern alteration methods that would provide a better fit (see Figure 4 for angles measured for pattern alterations). Using traditional techniques, measures of circumference and vertical length were used to alter the length and width of the pattern. Angle measurements were then used to relate the circumference measurements to each other (Heisey, Brown & Johnson, 1986).

Brinson (1977) compared the traditional method of pattern alteration with an experimental method based on angles measured from somatographs. This method was applied to the alteration of bodices and skirts. Douty and Ziegler (1980) looked at body proportions and angles to determine alterations for muslin dresses. Pouliot (1980) altered pants patterns by measuring the angles of the lower body and Lesko (1982) altered bodice patterns by measuring the angles of upper body contours. This method was also used by Brackelsberg, Farrel-Beck and Winakor (1986) who altered attached bodices and skirts. Similar methods have been used by Terry (1968) who noted figure irregularities visible in a somatograph

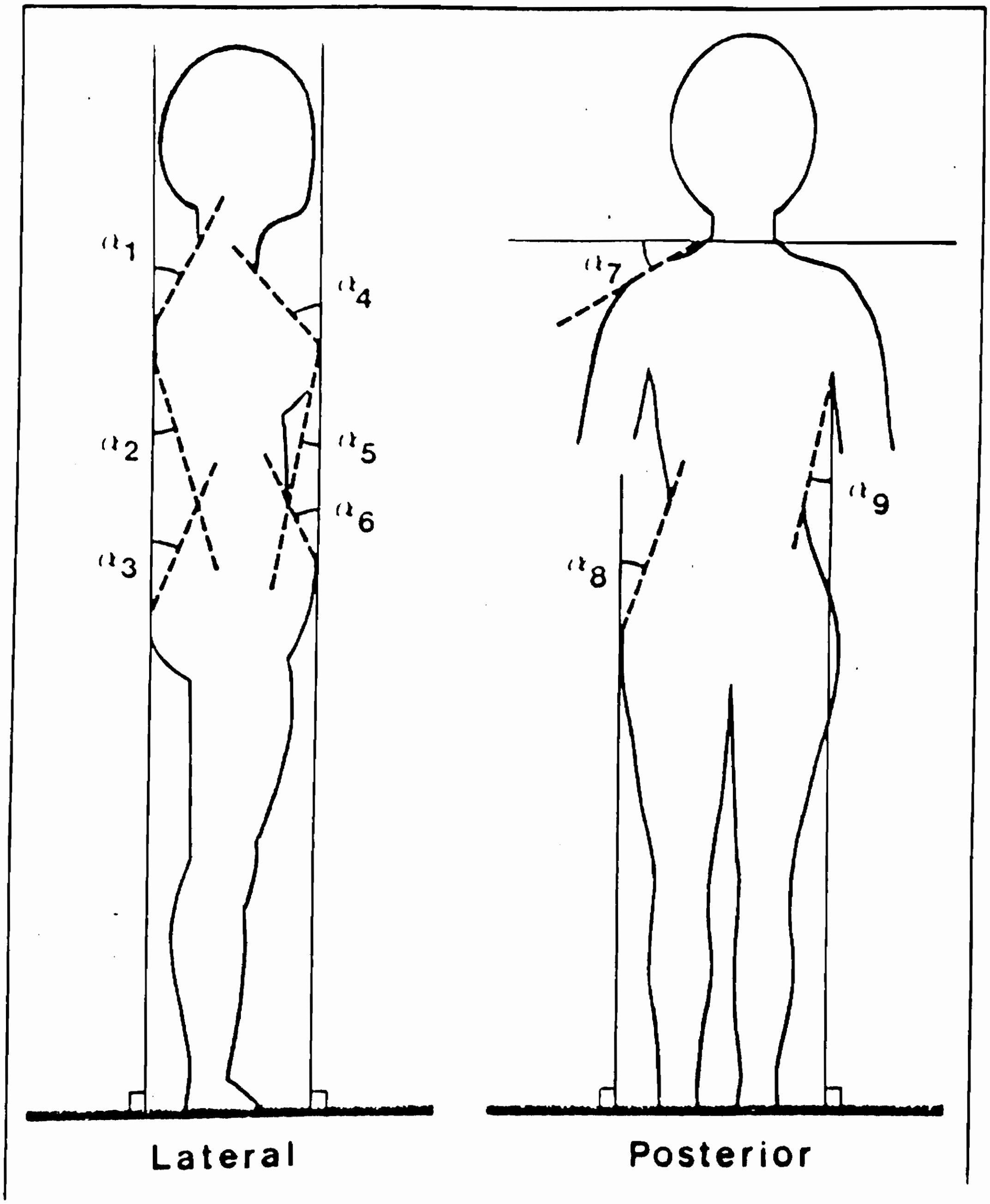

Figure 4. Angles of the body measured in somatometry pattern alteration methods

Note. From "A mathematical analysis of the graphic somatometry method of pattern alteration" by F.L. Heisey, P. Brown, & R.F. Johnson, 1986, AHEA, Washington, D.C., 15, p. 116.

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and used this information to predict necessary alterations. Philipsz (1962) and Reed (1963) traced the side hip curve and used this information to perform pattern alterations.

The research that has been done using somatographs has focussed on extracting two dimensional information from a photograph for use in altering two-dimensional patterns which are used to encircle the three-dimensional body. An application of two-dimensional information to a three-dimensional object requires that certain assumptions be made about the geometry of the 3-D object (Heisey, 1984). These methods of pattern alteration, although an improvement over traditional methods, are still based on many assumptions in order to translate 2-D information to the 3-D body.

Describing the human body with traditional anthropometric measurements has its limitations. Regular solid objects can be quantified with linear two-dimensional measurements. The human body, however, is an irregular, three-dimensional form "...which limits the efficacy of two-dimensional parameters for comprehensive and unambiguous quantification of body form" (Herron, 1972, p. 80). Even a large number of measurements describing body length, width, and circumference (all 2-D) do not supply details about the three-dimensional form.

Anthropometric measurements are quantifiable measures of body dimensions within one plane only. The numerical value assigned to any girth measurement conveys no information about the distribution of the mass within the perimeter of the girth (see Figure 5). There is no information which specifies location of contours. Length and breadth measurements as well dictate an assumed straight line measurement with

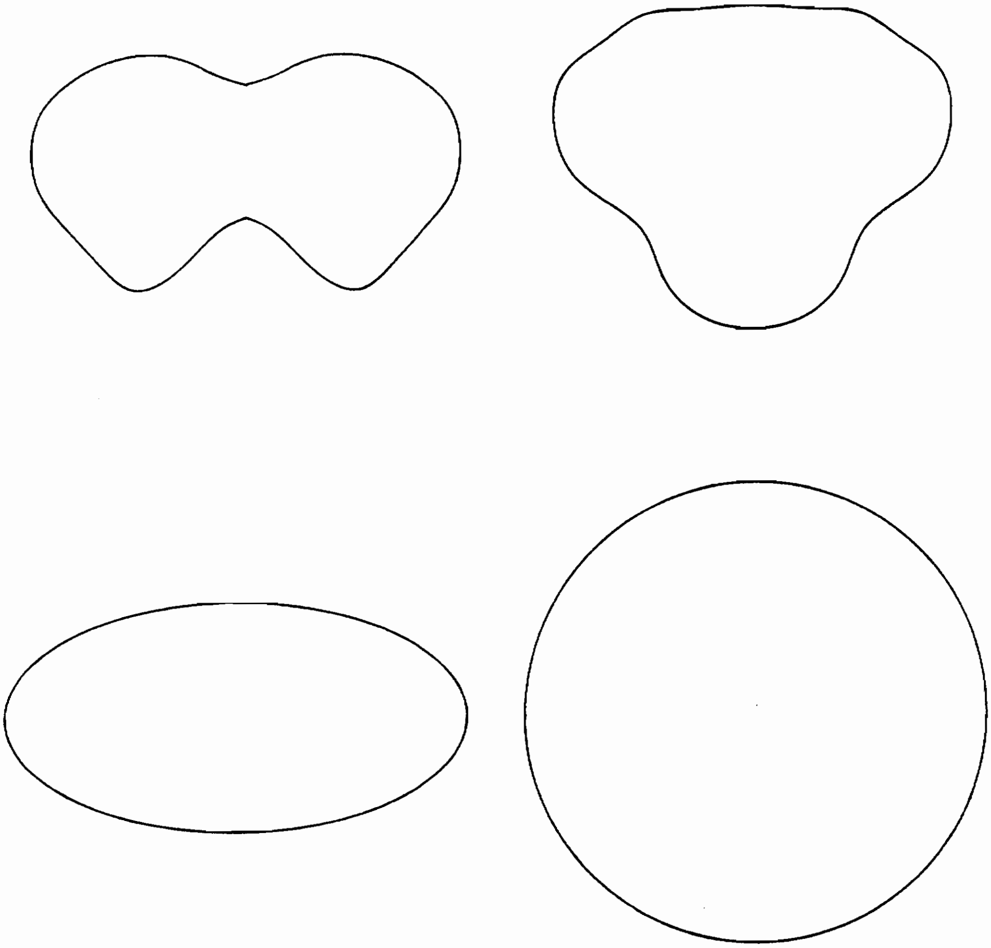


Figure 5 . Variations in location of mass with equal circumferences

no indication of curves or angles that may be encompassed. In trying to describe the form of the body this information is of limited value. The limitations of two-dimensional measurements lie not only in the lack of contour information supplied but also in the difficulty of relating one two-dimensional measurement to another (see Figure 6). Linear two-dimensional measurements are of limited value when defining a complex three-dimensional object such as the human body. Obtaining a comprehensive and unambiguous quantification of the body form requires considerable interpolation when using only two-dimensional data (Herron, 1972). The continued use of "...'tape and caliper' methods is helping to perpetuate certain information gaps" (Herron, 1972, p. 80).

Although using indirect means of obtaining information, such as photography, offered many advantages in taking anthropometric measurements there were several factors that required special consideration. In an effort to establish the use of photography as a quantifiable research tool anthropologists researched these issues.

In order to collect data from photographs of the body it is necessary to first mark anatomical landmarks on the skin. The same landmarks that are used with traditional anthropometry are also used for this purpose with the added stipulation that they be visible in a photograph. When anatomical points are used as references for taking measurements from a photograph the measurements can be as accurate as those taken directly on the individual (Gavan, Washburn & Lewis, 1952).

A standardized pose, where all subjects assume the same body stance and limb positions, usually has been used for photographs that are used for data collection. Most studies have been done using the standard (or

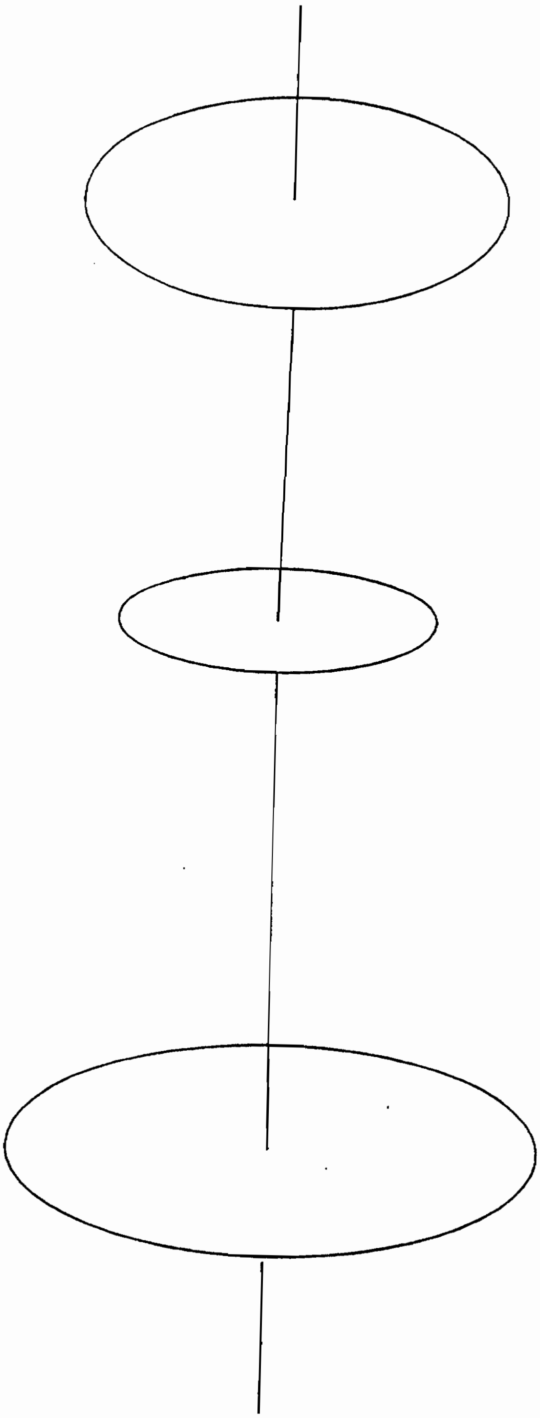
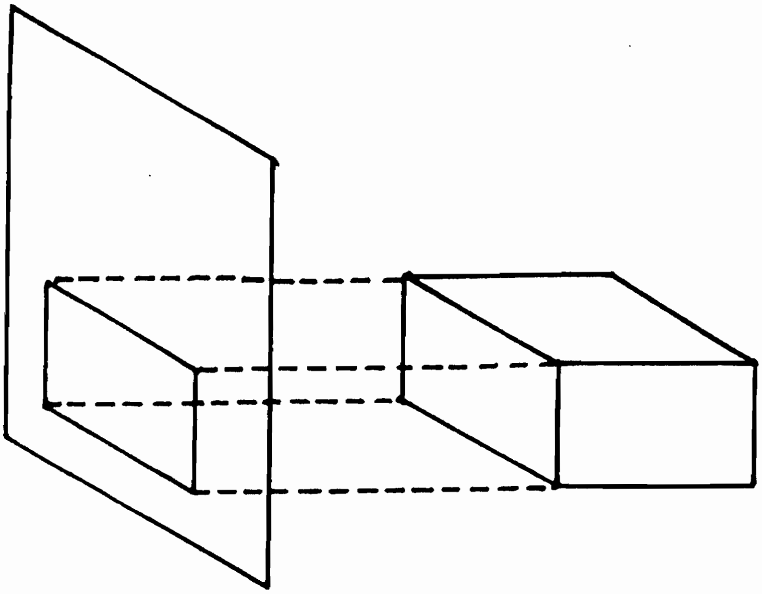


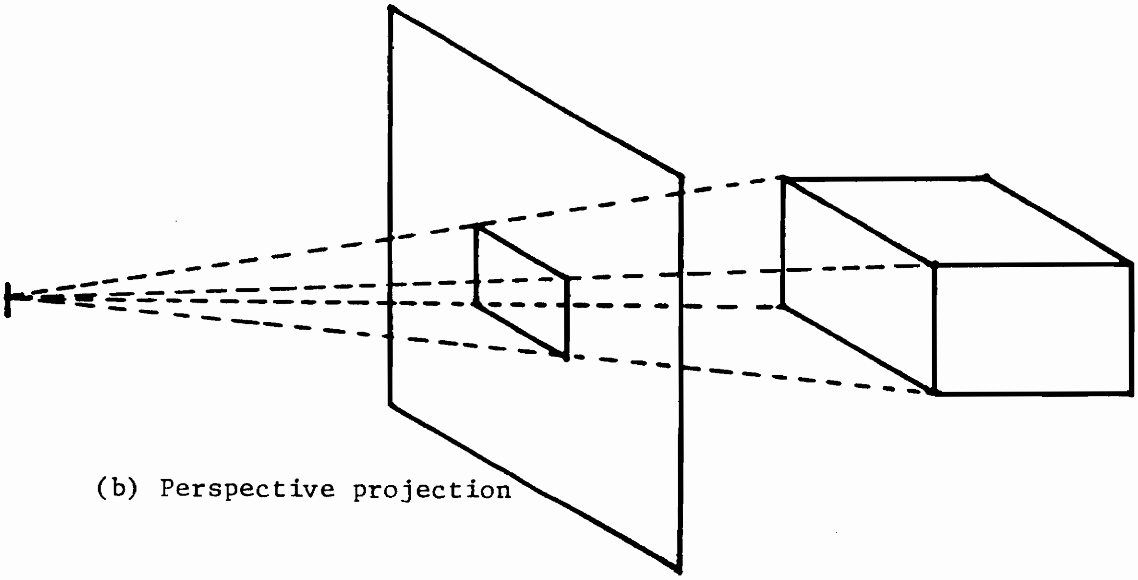
Figure 6. Assumed concentricity in relating two-dimensional measurements

classical) anatomical position. In the standard anatomical position the subject stands erect with the weight evenly distributed on both feet, heels close together, legs and torso straight (but without stiffness), and head erect with the line of vision parallel to the floor. The arms hang straight but loosely at the sides with palms alongside but not touching the thighs (McConville & Laubach, 1978). A standardized posture "...assures that the variation found in body size within a group is truly that associated with body size and not a compounding of this variance by differences in body stance" (McConville & Laubach, 1978, p. III-6). On the other hand, by requiring all subjects to assume the same stance it is impossible to investigate the 'real world' variability that occurs in posture (Reynolds, 1980).

The very process of using a camera to capture a two-dimensional image of a three-dimensional object requires a certain amount of interpretation. An engineering drawing captures the image of a three-dimensional object in an orthogonal projection (see Figure 7a). Since the lines projecting the actual object onto the reference plane are perpendicular to the object, the size of the object on the reference plane will always be the same actual size (Myklebust, Pennington & Dhande, 1989). A photograph, however, is actually a perspective projection of an object (see Figure 7b). The lines projecting from the actual object converge at the camera lens. The image captured on the reference plane (photograph) is distorted by the parallax which occurs. The photographic image is always smaller than the true object unless the camera lens is at infinity (Gavan et. al, 1952). This type of error can be reduced to an acceptable level by using a long lens-to-subject



(a) Orthogonal projection



(b) Perspective projection

Figure 7. Projection of a three-dimensional object onto a plane

distance (see Figure 8). Anthropologists researching this problem advise using a distance of at least twenty feet. Some anthropometric studies of this type have been done using distances up to forty feet.

There are both advantages and disadvantages of using a photograph to obtain quantifiable measurements of the body. One photograph captures many body dimensions and serves as a permanent record of the body which can be studied over a period of time. The problem of subject fatigue is also eliminated. Taking measurements from photographs is a non-invasive process and does not disrupt the natural position of the body. Problems due to personal bias and error in measurements could also be eliminated with this process.

The disadvantages of using measurement methods which are based on the use of photography are that these methods rely on the interpretation of the two-dimensional image of a three-dimensional object. The diffuse nature of the human body makes this interpretation even more difficult. The body is not an object made up of flat sides with easily identifiable corners. Determining the exact edge of the body surface is an approximation at best. Some researchers have tried to model the body as polyhedra (Appel & Stein, 1972) requiring a description of the object in terms of vertices, edges, and faces. This type of modeling does not handle curved surfaces and more complex objects and results in a substantial compression of the data (Bhanu, 1984).

Methods based on photography have an additional limitation which may be a problem depending on the purpose of the data collection. Photographs can only account for the exterior of the body without any consideration for the degree of compressability of soft body parts

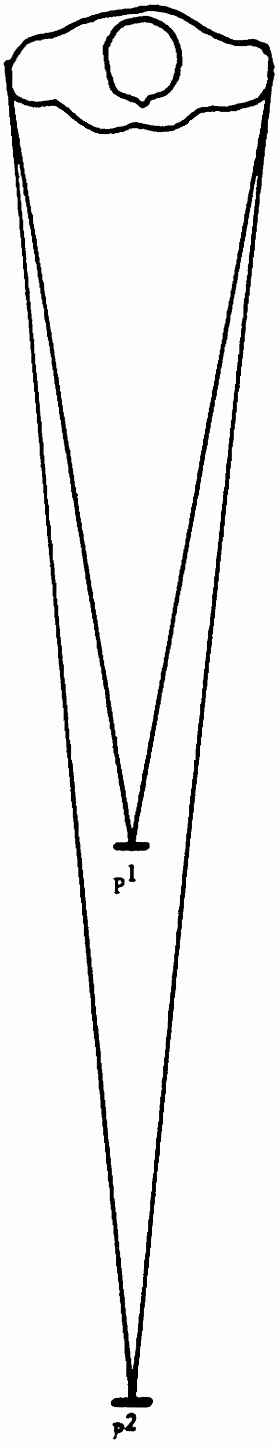


Figure 8. Overhead view of a body being photographed with camera at point P^1 and decrease in parallax with camera at point P^2

(Jurgens, 1980).

The photographic methods cited thus far have dealt for the most part with either a subjective analysis of the total body form or with obtaining two-dimensional body measurements. In locating points on the body surface these methods are capable of supplying only the x and y coordinates. The third dimension (or the z coordinate) is still missing. The piece of information which is relevant in determining the position (x, y, z) of a point in space is the range information, i.e., the distance from the object to the camera or any arbitrary source.

For any study involving measurement of the human body it is the proposed application of the design problem which determines the sample to be surveyed and the information to be gathered (Stoudt, 1980). The research proposed by this study requires the compilation of a new data base which reflects more information than that which is provided by traditional anthropometric studies. A method of measuring in three dimensions is required for this study.

Methods of Measuring the Body in Three Dimensions

Three-dimensional analysis of the body can be accomplished either by directly contacting the body with the measuring instrument or through indirect (non-contact) means. Technological progress is evident in the changing methods by which the body form has been analyzed over many decades. Originally, it was necessary to establish physical contact between the body and the measuring instrument in order to obtain human body measurements. This period, however, was followed by one in which researchers discovered the advantages of non-contact methods. In non-contact methods, instead of the measuring instrument actually coming into contact with the body a medium such as light, lasers, or sound waves is directed at the body. Whether a method of measurement is direct or indirect (contact or non-contact), the same information is derived, i.e., the range information. A chart of the various three-dimensional measuring methods to be covered in this paper and how they are related is provided in Figure 9.

Symbolizing three-dimensional objects in other than pictoral form is difficult. Many methods which have been used actually produce only a rough approximation of the object (Robinson, Sale, Morrison & Muekrcke, 1984).

In order to specify the three-dimensional quality of an object a frame of reference must be established. "Three-dimensional anthropometry is the measurement of points on the human body in a well-defined vector space" (Reynolds, 1980, p. 26). The most familiar frame of reference used to specify points defining the surfaces of an object in space is the Cartesian Coordinate system. In this system the coordinates of a point in space are the distances from the point to each of three intersecting, mutually perpendicular planes (American Heritage Dictionary, 1976). The data, specified in x, y, and z coordinates are referenced within a fixed axis system. By using this reference system any conceivable point in space can be specifically located and related to any other point(s).

Contact Three-Dimensional Analysis

The earliest three-dimensional measuring devices relied heavily on

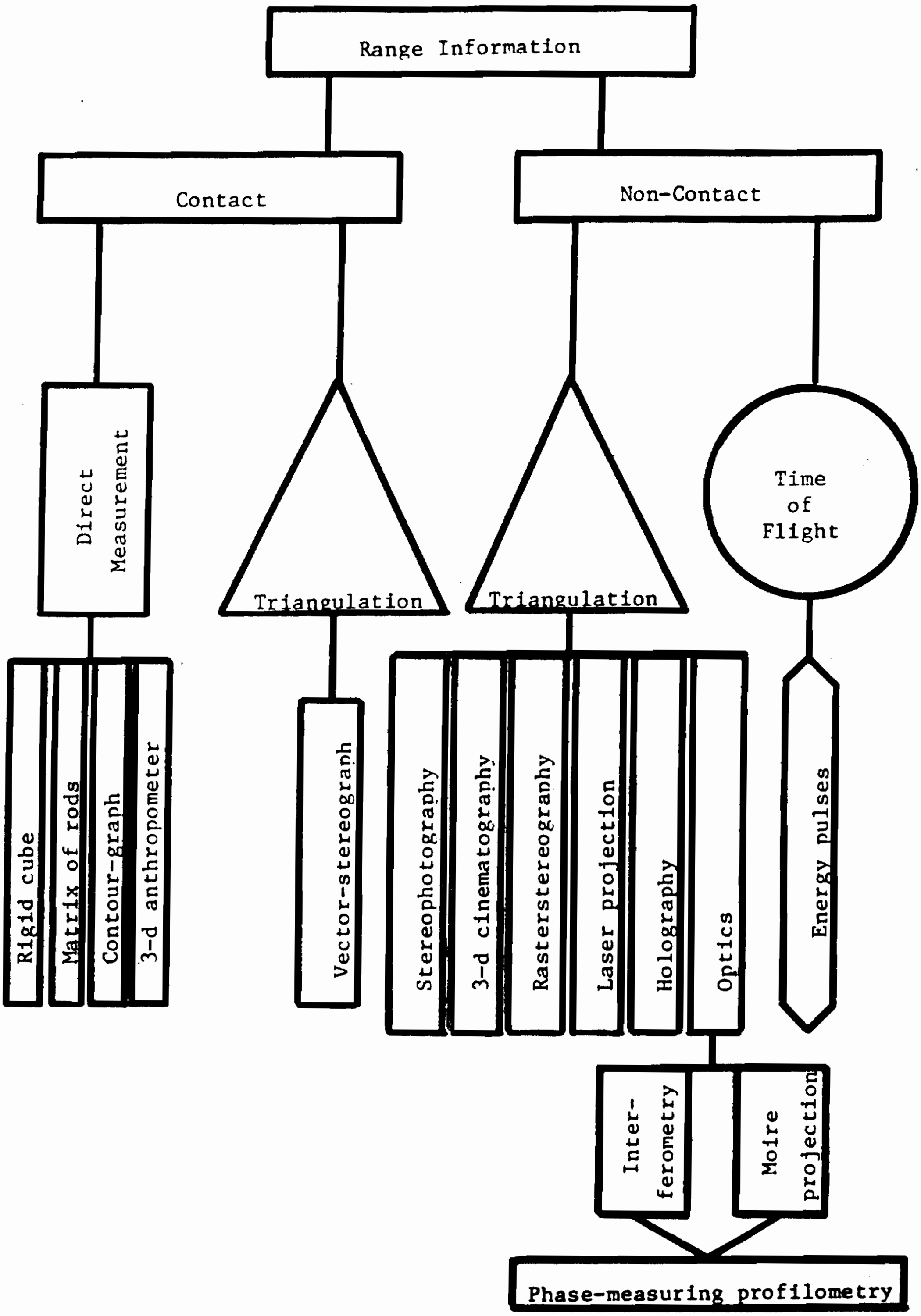


Figure 9. Framework for conceptualizing three-dimensional measurement methods for the human body

the use of the Cartesian Coordinate reference system, to the point of physically enclosing the object to be measured in a cube representing the x, y, and z axes. After this type of reference system is established measurements can be mechanically taken from the reference plane to any point marked on the body. In these types of methods the body is directly contacted by the measuring instrument. The physical contact methods are sometimes referred to as direct biostereometry or biostereometrics (Ignazi, Mollard and, Coblentz, 1980). In biostereometry three-dimensional analysis of the body is based on the principles of analytical geometry (Herron, 1972).

By placing rigid walls on two or more sides of the body any point on the body surface can be located by measuring the distance between each rigid wall and the point. Lange's method (1976) utilizes this type of cube with cords attached to the walls to measure the x, y, and z distances to body points. In the Morant technique, a set of grids is attached to the corner of two orthogonal vertical walls. The subject is placed in front of the grid and then distances are measured between body landmarks and the grid (see Figure 10).

Lovesey (1974) used a physical contact method in measuring the human face. The method is comprised of a matrix of rods held in a metal plate and positioned in front of the subject's face. The rods are pushed through the plate until they contact the facial tissue. By reading the position of the rod in the plate the coordinates of each point can be determined.

A contour-graph instrument was developed by Abdel-Aziz and Herron (1974) to measure the shape and volume of an amputation stump. The

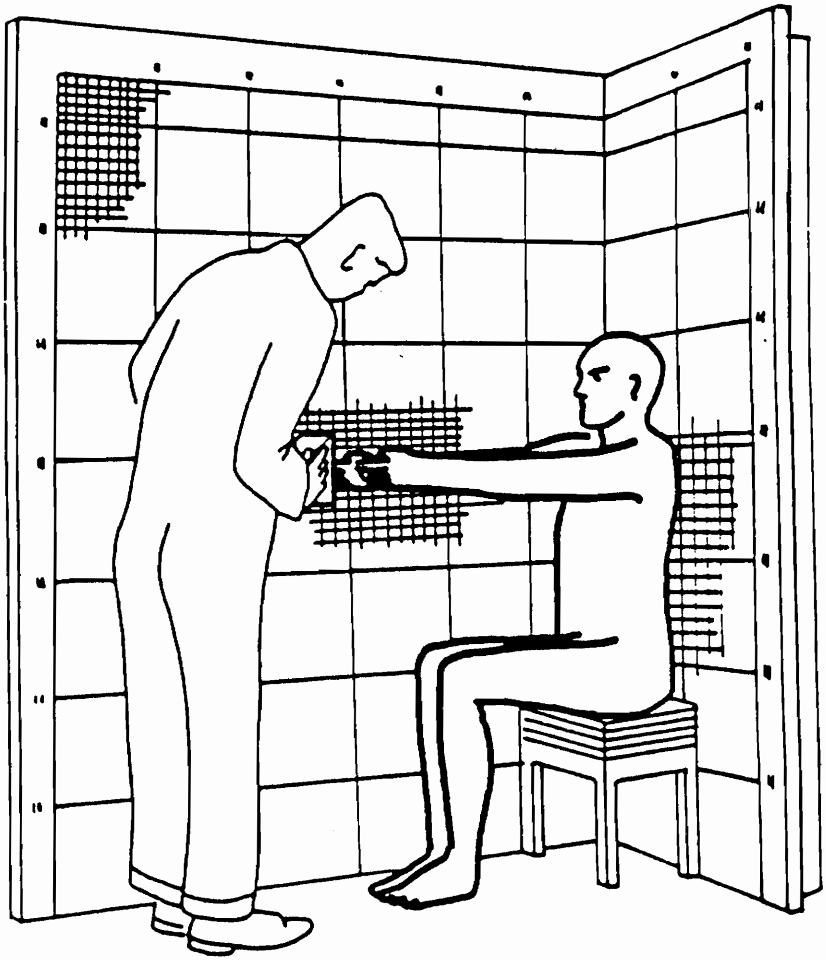


Figure 10. The Morant technique of three-dimensional measuring

Note. From *Engineering Physiology* (p. 9) by K.H.E. Kroemer, H.J. Kroemer, K.E. Kroemer-Elbert, 1986, Amsterdam: Elsevier Press.

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instrument records the cross-section of the amputated stump by employing a "feeler." The feeler rotates 360° around the stump while maintaining gentle contact with the skin surface. Cross-sectional data can be represented either graphically or numerically.

A mechanical three-dimensional anthropometer was used in a 1972 study to collect data on 281 female flight attendant trainees (see Figure 11). Although these data do not describe the body surface, they do locate body landmarks in three-dimensional space. The relationship between these landmarks describes the posture of each female subject (Reynolds, 1980).

The measuring stand used in the Hutchinson & Munden (1978a & b) research is another type of three-dimensional anthropometer. It was built for the study with vertical uprights equipped with adjustable cross bars (see Figure 12). The upright member is used as a baseline for obtaining depth measurements of the body. Special adjustable protractors are also used to determine angles in the shoulder area. Hutchinson & Munden measured the shoulder slope and forward angle of the shoulder both by using the protractors and by measuring distances with the measuring frame and then calculating the angles. These angles derived by the methods corresponded closely with each other.

Physical contact methods such as those described above are the simplest approach to the three-dimensional measurement of body shape. Readings are taken directly from an instrument after it is properly positioned in relation to the body. These methods are also the most tedious, cumbersome and time-consuming. Since each of these methods requires positioning of an instrument and recording of data to be done

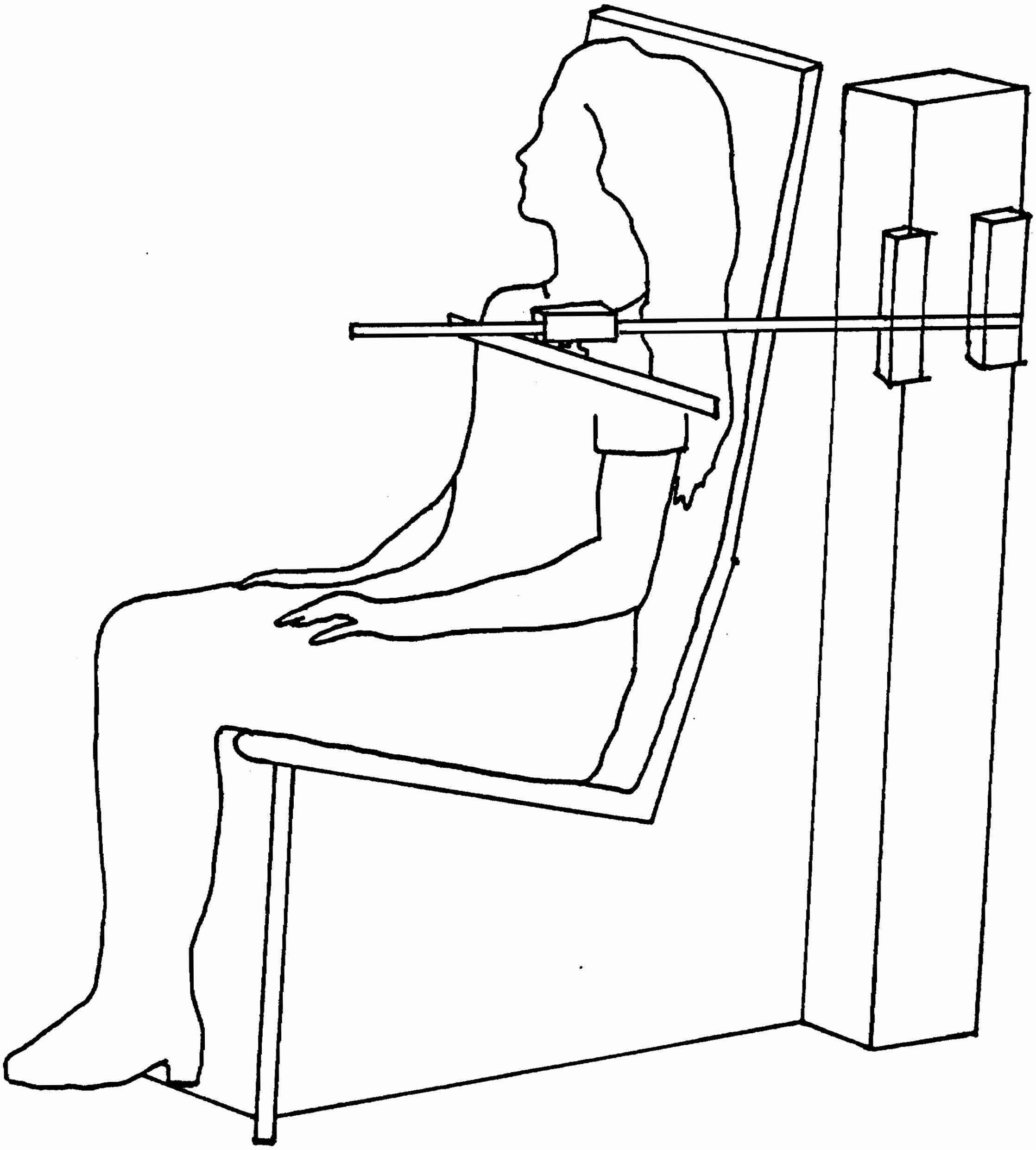

Figure 11. 3-d anthropometer used in 1972 FAA study

Note. "The human machine in three dimensions: Implications for measurement and analysis" by H.M. Reynolds, 1980, in R. Easterby, K.H.E. Kroemer, and D.B. Chaffin (Eds.), Anthropometry and Biomechanics, Theory and Application, New York: Plenum Press, p. 28.

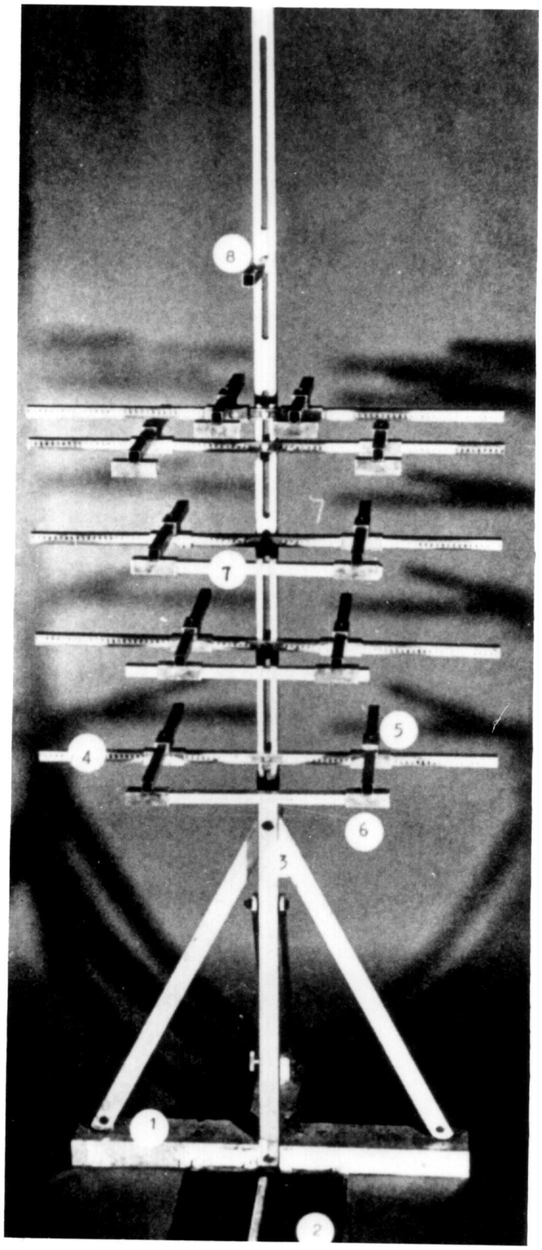

Figure 12. Measuring stand used in Hutchinson & Munden study

Note. From "The geometrical requirements of patterns for women's garments to achieve satisfactory fit" Part I by R. Hutchinson & D.L. Munden, 1978a, Clothing Research Journal, 6, p. 75.

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by a human operator the likelihood of human error is much greater.

Triangulation Methods

"It is a principle of geometry that if three vectors meeting at a point are known, it is possible to define that point in space" (Burwell, 1977, p. 57). This is the principle upon which the theory of triangulation is based. Triangulation methods utilize the principles of analytic geometry to derive range information (see Figure 13). Triangulation was developed for use in navigation and surveying. It was only later that it was applied to the body and medical problems.

Most methods which employ the use of triangulation are non-contact methods of measurement (see Figure 14 for a chart of non-contact triangulation methods). Because contact with the body is not established, determining the distance from a reference plane such as the camera or the wall of a cube must be accomplished through calculations.

However, at least one method which involves physically contacting the body employs the triangulation principle. The vector-stereograph was used by Morris and Harris (1976) to record the size and shape of the trunk's surface in scoliosis patients. The frame of the apparatus contains feed bobbins and string attached to a vector focal-point. The focal-point is manually moved over the back of each subject and the length and direction of each string is recorded. These vectors are stored on magnetic tape and used to produce contour maps, cross sections and perspectives of the back.

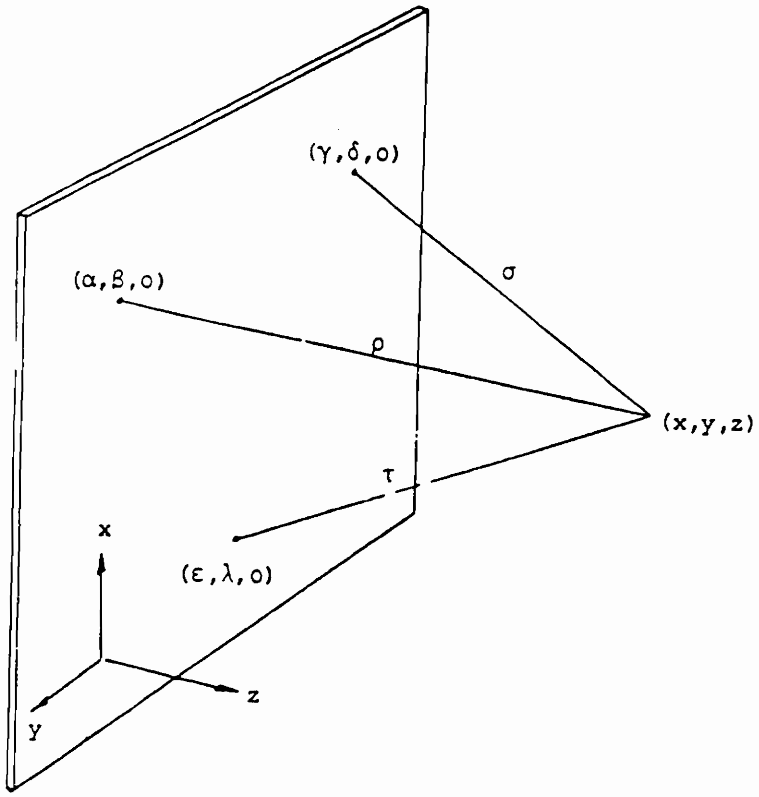

Figure 13. Analytic geometry principles governing methods based on triangulation

Note. From "Biostereometrics, shape replication and orthopaedics" by R.G. Burwell, 1977, Proceedings of the Orthopaedic Engineering Conference, p. 56.

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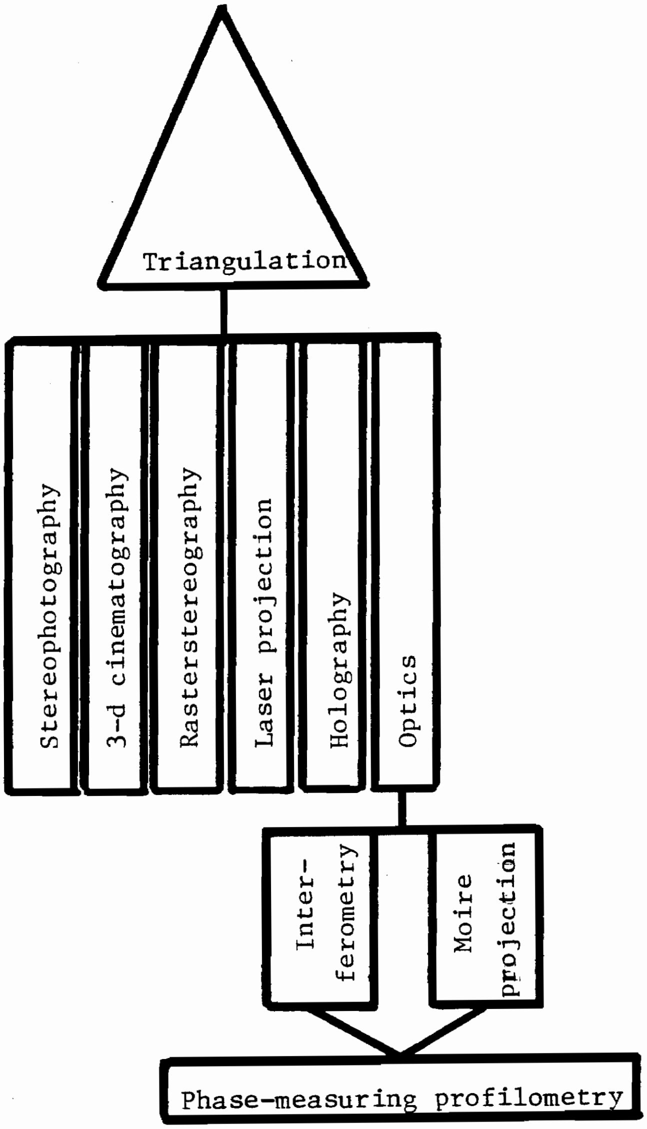

Figure 14. Framework for conceptualizing non-contact three-dimensional measurement methods based on triangulation

Non-Contact Three-Dimensional Analysis

Indirect measurement methods have an advantage over direct measurement methods simply because they do not involve contacting the body with the instrument itself. Instead of the instrument coming into contact with the body a medium is projected to the surface being measured. Whereas the contact of an instrument against the skin may cause a reaction the contact of a medium will not.

Triangulation Methods

Stereo Images

Stereo imaging, or stereophotography, involves looking at an object simultaneously from two (or more) points of view (Herron, 1972). The science of measuring and describing the three-dimensional form of biological objects in mathematical terms is known as biostereometrics (Whittle, Herron & Cuzzi, 1977).

The layout for stereophotogrammetry is shown in Figure 15. Simultaneous photographs are taken of the subject by paired cameras, usually from both front and back. "The subject stands between two control stands, which provide dimensional information in the three orthogonal axes" (Whittle et al., 1977, p. 198). The photographs are taken with an overlap so that all points on the object are visible in each photograph (Hallert, 1960). The paired overlapping photographs are oriented in a stereoplotter which forms a 3-D model of the object. The 3-D model is formed by using projectors which are given the same relative orientation as the camera had in the moments of exposure. The corresponding rays from the projectors will intersect.

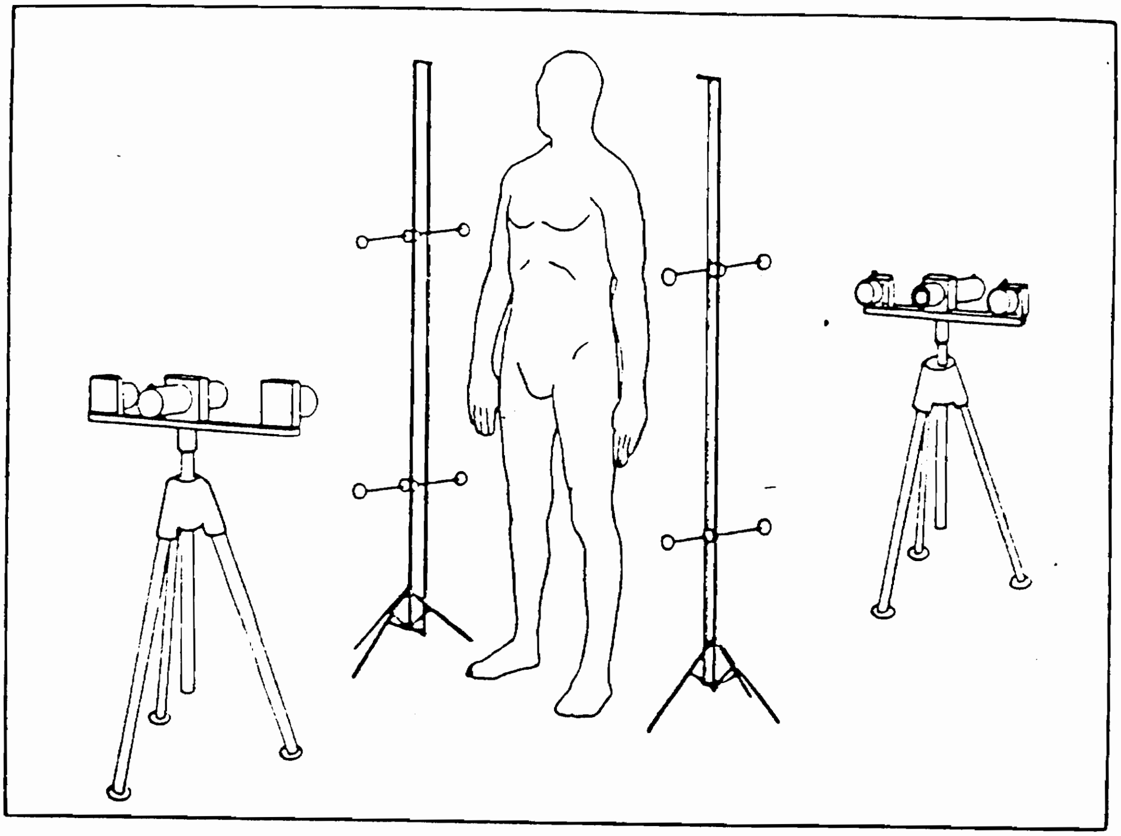

Figure 15. The set up for stereophotogrammetry

Note. From "A portable dual camera system for biostereometrics" by J.E. Hugg, 1974, Proceedings of the Symposium of Commission V, International Society for Photogrammetry on Biomedical and Bioengineering Applications of Photogrammetry, p. 121.

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> The bundle of rays (see Figure 16) from the photography are reconstructed by illumination of the pictures 'from behind.' All such intersection points will together form an optical model, geometrically similar to the photographed object. The scale of this model depends upon the base between the projectors and can be varied by changing the base. ...The model can thereafter be regarded as the original object as far as technical measurement requirements are concerned (Hallert, 1960, pp. 5-6).

Orientation of the images in the stereoplotter is based on known constants such as the distance between the two camera lenses, the internal camera geometry, the distance between known points in the photograph, and inclination of the camera axes. By identifying the same point in two paired photos the relative geometry of the cameras can be used to perform the actual triangulation which determines the x, y, z surface point coordinates (Posdamer & Altschuler, 1982).

As an aid in identifying the same point in each photograph of a pair, some stereometric systems make use of a Surface Contrast Optical Projector (SCOP). The SCOP projects a fine line random pattern onto the otherwise undetailed surface of the skin (see Figure 17). This projection is synchronized with the camera shutters (Hugg, 1974).

The process of data reduction required by this method is rather involved and complex. However, the process yields as many spatial points on the body as are required by the problem being investigated. Thousands of points on the body were derived from the analyzed data when the Skylab crewmen were analyzed using this method. The 3-D coordinates were then punched on IBM cards for subsequent computer analysis (Whittle

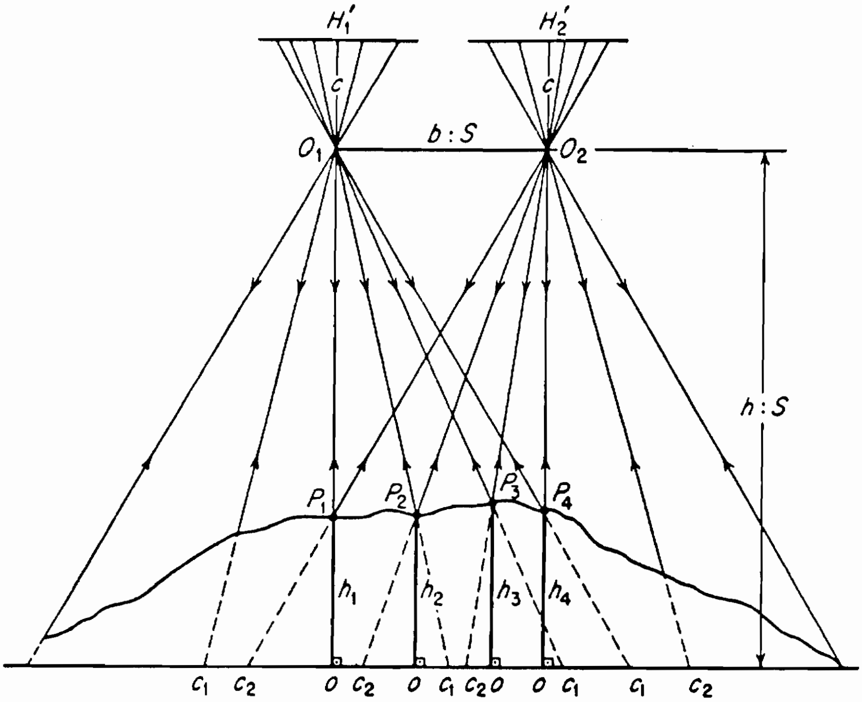

Figure 16. Rays from points P to P being projected into the cameras at points O and O in bundles

Note. From Photogrammetry, Basic Principles and General Survey, by B. Hallert, 1960, New York: McGraw-Hill Book Company, p. 6.

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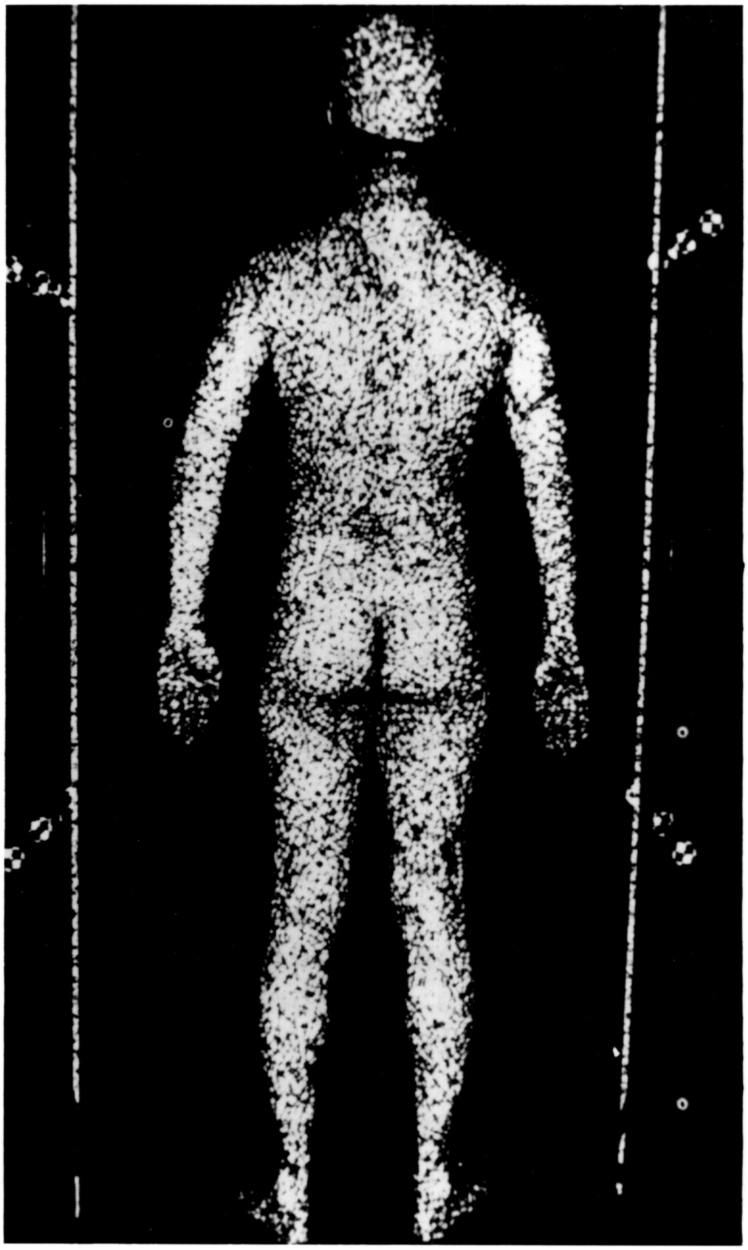

Figure 17. SCOP fine line pattern projected onto surface of skin to provide contrast

Note. From "A portable dual camera system for biostereometrics" by J. E. Hugg, Biostereometrics '74, American Society for Photogrammetry, p. 123, Figure 3.

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et al., 1977). From this set of points a variety of data may be generated by a computer. The points can be plotted to produce a contour map (see Figure 18), cross sections (see Figure 19), or a composite of body sections (see Figure 20). Areas, volumes and surface areas may be computed. The body may be analyzed in segments or as a whole. The accuracy of the data derived from stereo-photogrammetric methods varies depending on several factors such as the amount of overlap between the photographs, the angle of the cameras, the base-to-distance ratio (base measurement of the object/distance of object from camera), and the type of camera and stereoplotter used (Karara, 1974).

The utility and accuracy of stereophotogrammetry was successfully demonstrated in the Skylab studies (Thornton, 1978). "...stereometric analysis, being a noncontact method, does not involve the compression of tissues, however small, which results from the use of a tape measure" (Whittle et al., 1977, p. 199). "...the stereoscopic photographs...are a permanent detailed record of body form, which may be reexamined at some future date to answer new questions, or to take advantage of the increased accuracy resulting from advances in technique" (Whittle, et al., 1977, p. 202).

This method requires the use of high precision cameras with calibrated internal geometry. The difficulty in using stereo images to compute the position of a point lies in the problem of identifying the same corresponding point in both images. The image positions of the corresponding points must then be measured and paired. In defining the surface of the body, an infinite number of points must be located. There is usually a tradeoff made between accuracy and any disparities

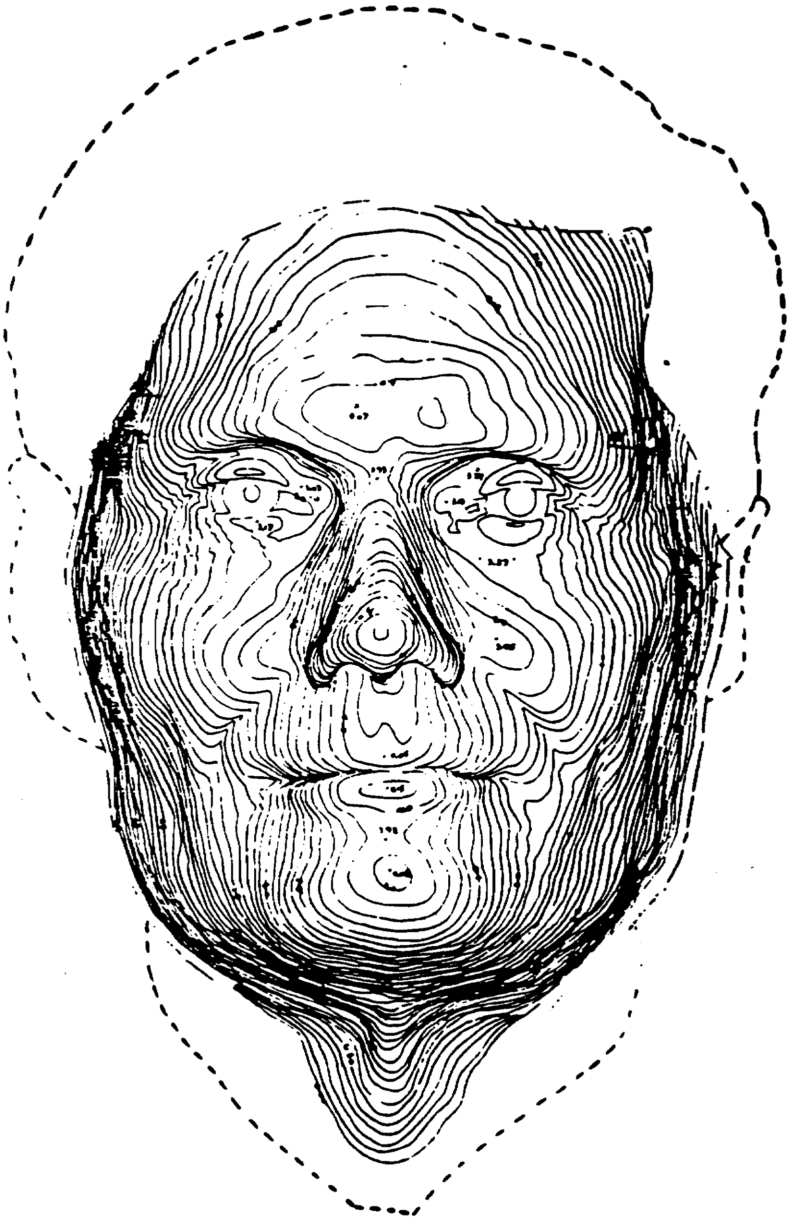

Figure 18. Contour map of a face plotted from digitized points by a photogrammetric process

Note. From "The replication of limbs and anatomical surfaces by machining from photogrammetric data" by J.P. Duncan, J. Foort &, S.G. Mair, Biostereometrics '74, American Society for Photogrammetry, p. 541, Fig. 16.

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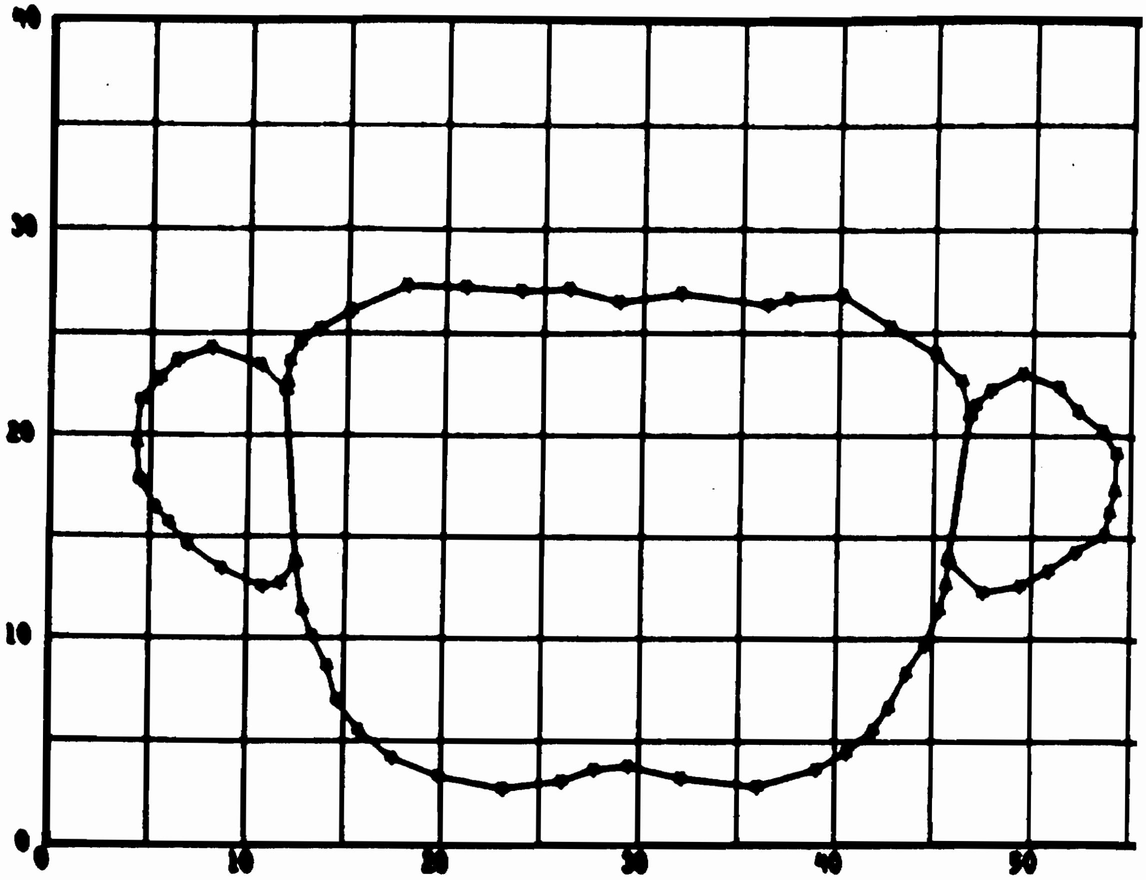

Figure 19. A cross section of the body at shoulder level generated by a computer from points derived from stereophotogrammetry

Note. From "Anthropometric changes in weightlessness" by W. Thornton, 1978, in Anthropometric Source Book, Vol. I: Anthropometry for Designers, p. I-41.

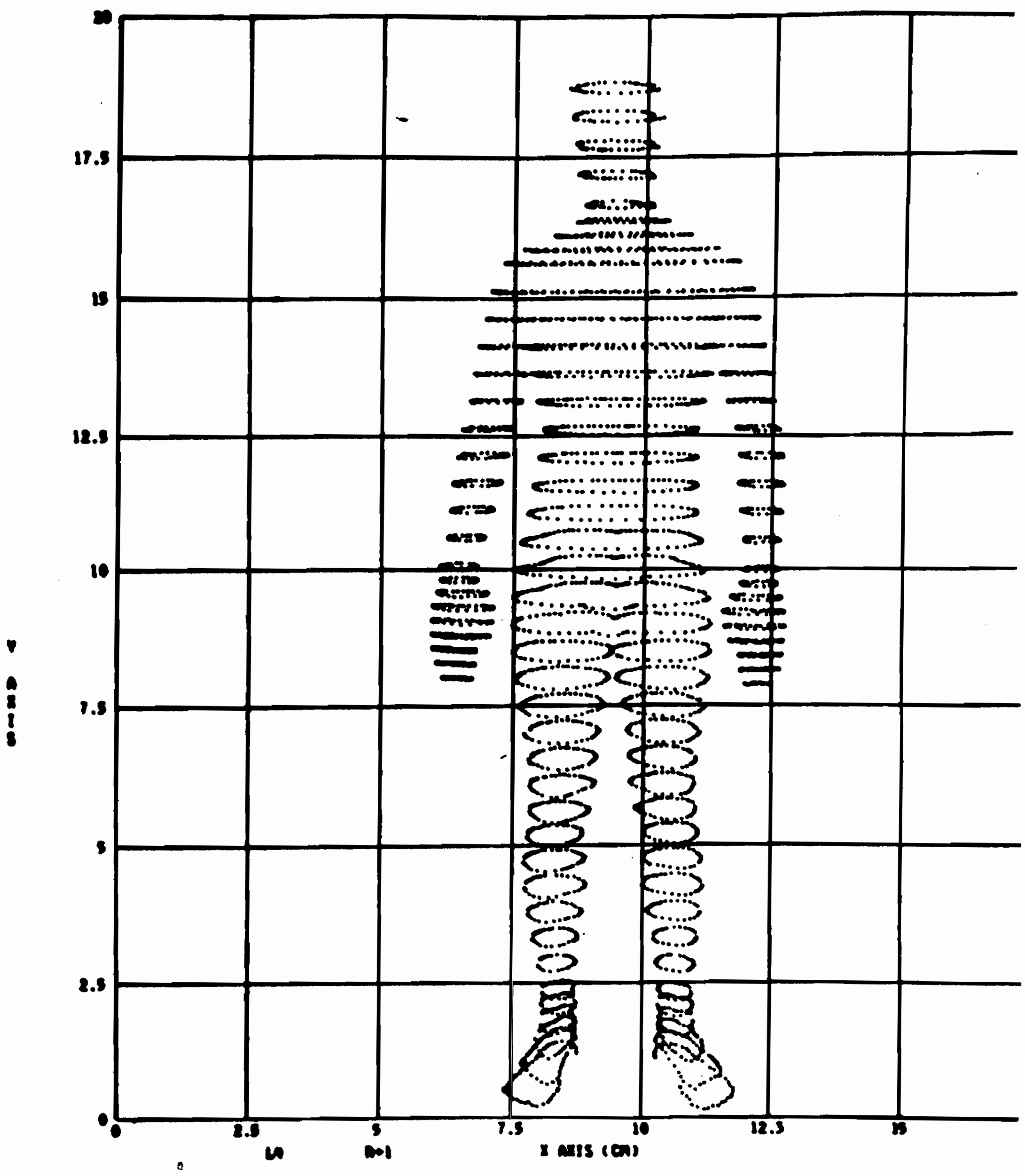

Figure 20. A composite of cross sections of the body made from stereophotogrammetry

Note. From "Anthropometric changes in weightlessness" by W. Thornton, 1978, in Anthropometric Source Book, Vol. I: Anthropometry for Designers, p.I-42.

between the two views (Yamashita, Oshina &, Yamaguchi, 1982). Some researchers have addressed this problem by actually marking landmarks and even grids on the surface of the body (Mollard, Sauvignon & Pineau, 1982; Garstein & Shaya, 1986).

This problem may be avoided by using specially controlled or encoded illumination. By projecting a collimated light beam (parallel waves), a laser beam diverged by a cylindrical lens, or a sheet of light from a slit projector onto the object being measured, every point of the surface of the object determines a ray in space. The coordinates of each point hit by the ray can then be determined by a trigonometric formula (Yamashita et al., 1982).

Three-Dimensional Cinematography

This method, like stereophotography, relies on the use of multiple images of the object to be measured. Earliest uses of this method required that the cameras be aligned along the orthogonal axes of the Cartesian Coordinate frame of reference. Refinements of the method, however, eliminated this requirement and allowed cameras to be placed without restriction (VanGheluwe, 1978). It is the use of a tri-axial reference frame (see Figure 21) that allows this type of flexibility.

The cameras are set up to obtain the best photographs of the object (a body) being measured. The reference frame is positioned so that it is within the field of vision of the cameras. All cameras are activated simultaneously to avoid positional shifts of the landmarks between pictures. The x and y coordinates of any arbitrary point on the body (either a characteristic landmark or electrode) can be digitized from the photographs. Processing of the data is done by a computer using

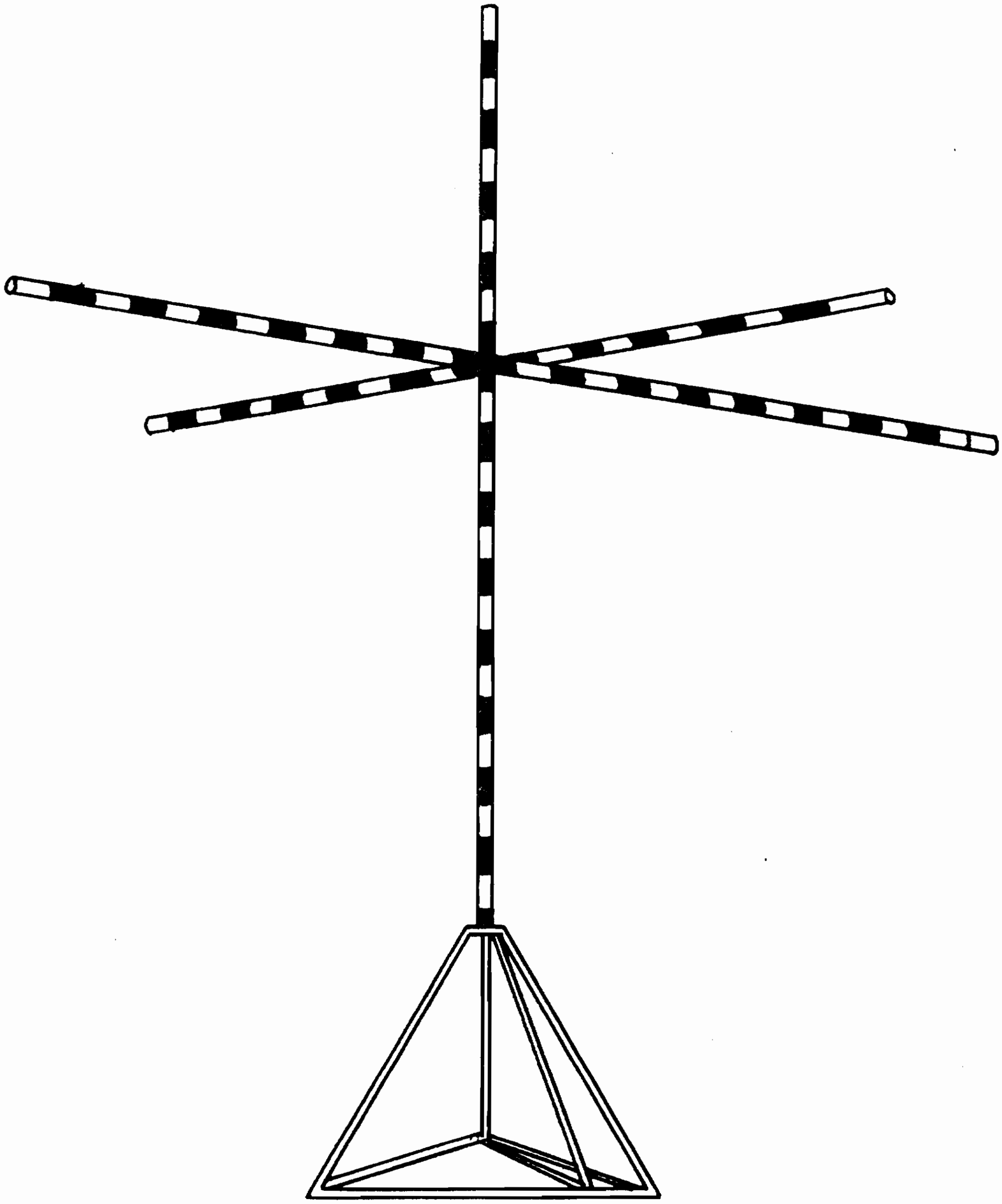

Figure 21. Tri-axial reference frame used with three-dimensional cinematography

Note. From "Computerized three-dimensional cinematography for any arbitrary camera setup" by B. VanGheluwe, 1978, in E.A. Asmussen & K. Jorgensen (Eds.) Biomechanics VI-A, Baltimore: University Park Press, p. 345.

information about the position and orientation of the cameras and the coordinates from the tri-axial reference frame. The result is a set of three-dimensional coordinates for these digitized points. The data are smoothed by a special computer program in which mathematical constraints are provided by a set of anthropometric measurements (Cornelis, VanGheluwe, Nyssen & VanDenBerghe, 1978).

When as many as eight cameras are used each point can be seen in at least three of the cameras instead of only two. This results in a significant increase in accuracy (Cornelis et al., 1978).

Although methods of this type are highly accurate they are difficult to automate and are therefore more time-consuming. The need for manual measurements in order to extrapolate data also makes this method more time-consuming and possibly less accurate (Kuhlman, 1988).

Rasterstereography

Rasterstereography is very similiar to stereophotography except instead of two cameras being used, one camera is replaced by a projector with a raster diapositive (see Figure 22). The direction of the light rays of one of the half images is reversed and replaced by the raster diapositive. The other half image is generated by the camera and contains the image of the object bearing the projected and distorted raster lines. Therefore, a stereoscopic image pair is still available from the raster diapositive and the camera image.

The three-dimensional information is obtained from the distortion of the projected raster lines and is therefore contained within a single image making stereoscopic vision unnecessary (Frobin & Hierholzer, 1983). Due to this fact, the problem of determining corresponding

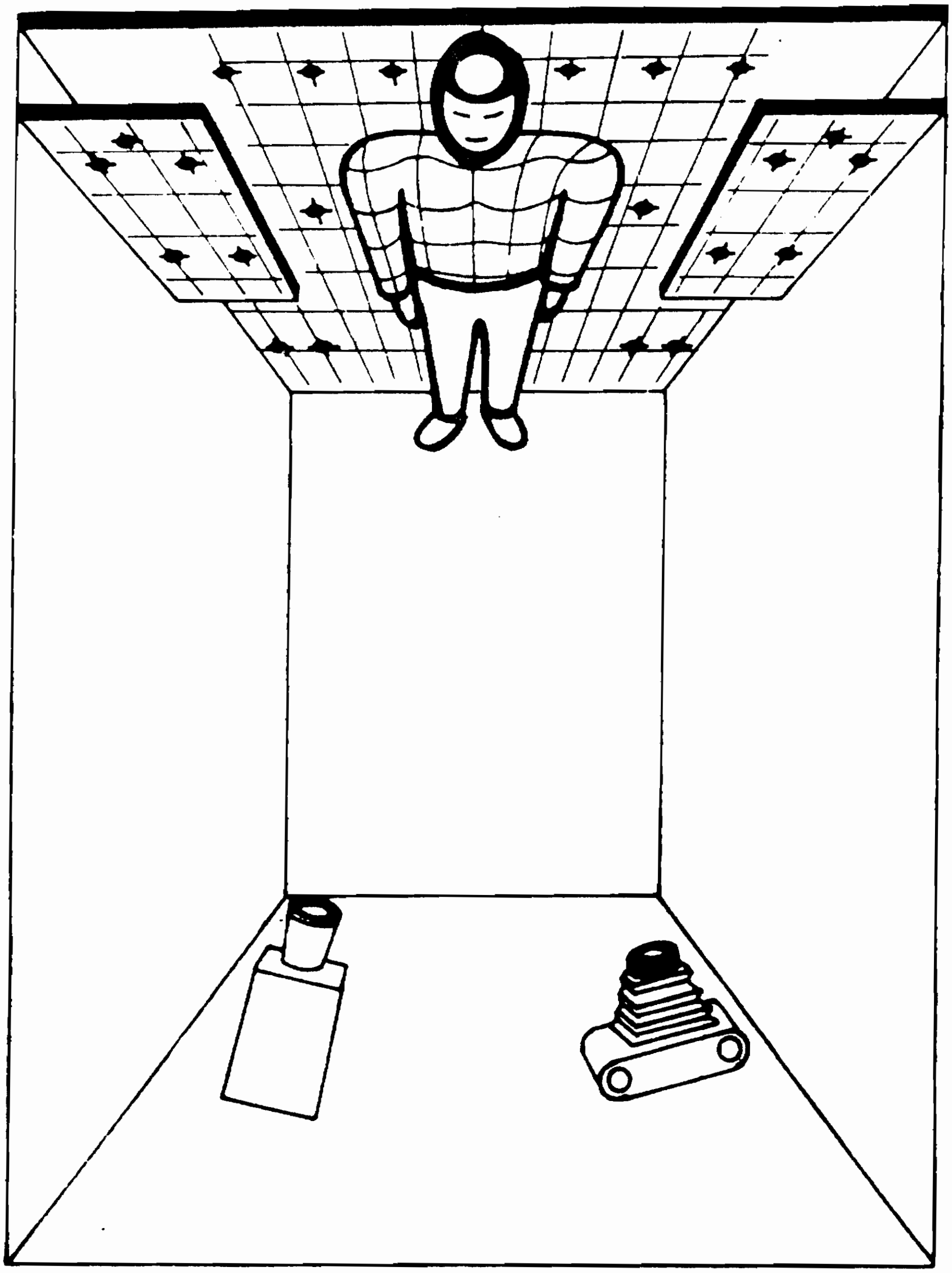

Figure 22. Experimental set up for the rasterstereographic method of measurement; subject above, camera and projector below

Note. From "A stereophotogrammetric method for the measurement of body surfaces using a projected grid" by W. Frobin & E. Hierholzer, 1978, Applications of Human Biostereometrics, Proceedings of the Society of Photo-Optical Instrumentation Engineers, 166, p. 40.

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points in a pair of photographs (as in stereophotography) is eliminated. Points may be objectively paired by determining the row and column number of the raster intersection. Points which fall between these raster lines may also be calculated by interpolation if the density of the raster lines is adequate with respect to the curvature of the surface being measured (Hierholzer & Frobin, 1980).

Horizontally-oriented raster lines are projected onto the body surface as well as onto control planes (see Figure 23). Luminous control points are located on the planes. Each raster line may be individually identified and measured. The x and y coordinates of the center of the control points may be measured and used as a basis for determining the coordinates of the control lines.

The same type of standard photogrammetric calibration procedures are used as in stereophotogrammetry. Since stereophotography, rasterstereography, and moire topography are all based on distance measurement by triangulation the depth resolution of these methods is also similar. However, rasterstereography and moire are limited to the close range. "A particular advantage (of this method) is the possibility of an easy automatic image processing" (Hierholzer & Frobin, 1980, p. 329).

Laser Projection

Projecting a laser beam onto the surface of an object makes it possible to locate in space any point on the object by locating the light spot of the laser beam on a matrix of diodes of the camera (Ignazi et al., 1980). The range information (or z coordinate) is obtained by telemetric measurement based on triangulation.

Figure 23. Projection of horizontally-oriented raster lines onto a body and control planes

Note. From "Automatic measurement of body surfaces using rasterstereography, Part I: Image scan and control point measurement" by W. Frobin & E. Hierholzer, Photogrammetric Engineering & Remote Sensing, 49, n. 3, p. 378, Fig. 1. (Reprinted with permission)

A laser is projected to the surface of the object to be measured and scanned. A camera, which is also focussed on the object, is equipped with line sensors and cylindrical lenses. The camera views the dot pattern that is produced by the projected laser. The x, y and, z coordinates of the laser spot can be measured for that point (or in multi-laser systems for each point) by triangulation.

Researchers at the Harry G. Armstrong Aerospace Medical Research Laboratory (Wright-Patterson AFB), use a low-powered, helium-neon laser scanner to collect human body measurements. A laser light is projected onto a body surface from the scanner which rotates around the person's body to collect measurements (personal correspondence, G. Zehner, January, 1989). An advantage of this system is that the absolute coordinates of the three-dimensional point are determined at high speed and no human intervention is required. A computer automatically processes the x, y and z coordinate information.

The time required to complete a scan of the entire body is a disadvantage of this method. Because the scanning process is quite time-consuming problems may arise due to subject motion (Kuhlman, 1988). Also, the question regarding the intensity of laser pulses which is detrimental to human subjects must be considered.

Holography

"Laser holography is a means of encoding an image of a three dimensional scene onto a two dimensional photographic plate" (Burwell, 1977, p. 65). An interference pattern is generated between a reference beam and the light reflected from the object. The plate is then illuminated with a laser or other coherent light source to produce a three-dimensional effect.

A hologram can be constructed and used very much like a stereometric model. However, because the hologram is an optical interference pattern both the object and the optical system must be dimensionally stable to a very high degree (measured in terms of a fraction of a wavelength) during the time of exposure. This requires that there be no vibration. This would be virtually impossible with a living human body. A hologram also requires the use of coherent light for illumination of both the object and the photographic plate. The developments in holography also restrict the size of the object to be measured to only a few inches in each of three dimensions.

Advances in laser holography have made it possible to use lower pulsed lasers which may make them increasingly safe for use with human subjects. However, the possibility of risk to human subjects must still be considered. Another problem associated with the use of holograms is that the extraction of numerical data with this method is difficult. A hologram would be a preferable method of measurement when three-dimensional information needed to be stored and later displayed (Mikhail, 1974).

Light Projection

The use of optics is well-suited for obtaining three-dimensional measurements especially with the human body. Optical methods are not only non-invasive, non-contact methods of measurement but the range information derived from these methods is highly accurate as well.

The problem of identifying corresponding points in two or more images, as experienced with stereophotography, can be avoided by using a projected light system. Originally, this method was based on the interference of light waves which are directed at the object to be measured. This method, known as interferometry, measures the interference between a reference wave and an experimental wave in order to determine wavelengths, wave velocities, distances, and directions.

1. Interferometry

Interference is the phenomenom of two or more waves of the same frequency combining to form a wave in which the disturbance at any point is the algebraic or vector sum of the disturbance due to the interfering waves at that point (American Heritage Dictionary, 1976). If the crest of one wave overlaps the crest of another wave the effects are added together. This type of interference is known as constructive interference. If the crest of one wave overlaps the trough of another their individual effects are reduced. This type of interference is known as destructive interference (Hewitt, 1989).

When an advancing wave front is stopped by a grating (a screen in which narrow parallel slits are cut) a circular wavelet spreads in all directions from these slits (Ford, 1968). Since each slit is the source of a circular wavelet the pattern of the emerging waves is in interference (see Figure 24). Where the wavelets are in phase when they meet the constructive interference a point of illumination is produced. Where the wavelets are completely out of phase the destructive interference produces a point of darkness. These light and dark fringes can be used to measure the irregularities of the surface of an object onto which they are projected. If the surface of the object were completely flat, the lines would be straight and parallel. Irregularities on a

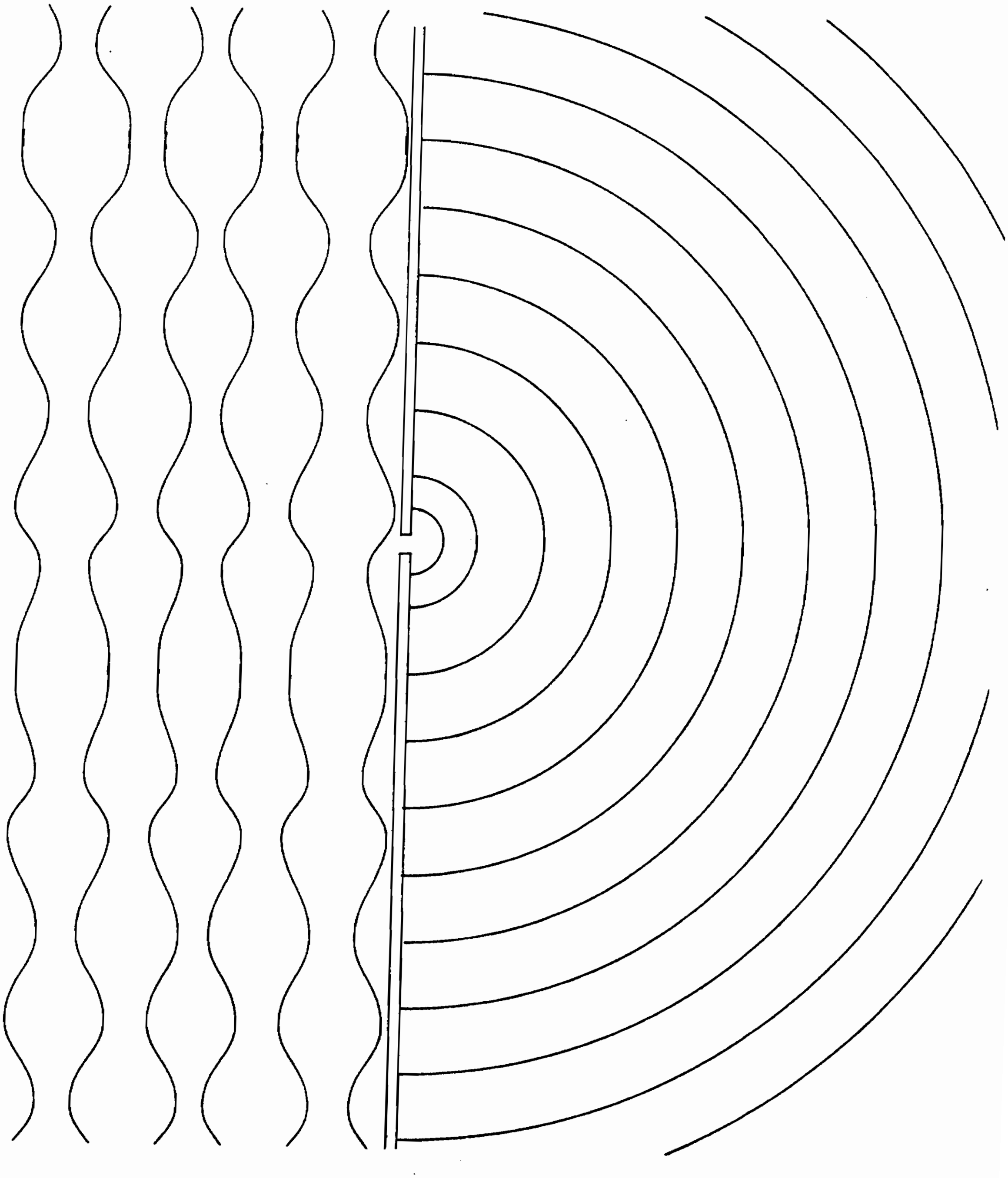

Figure 24. Circular wavelets formed as a wave front passes through a slit in the grating

surface, however, produce contour lines resembling those on a topographical map (Young, 1976).

2. Projection Moire

The actual interference of waves as a means of measuring the surface of objects was replaced by methods which mechanically created the interference pattern. The new optical method only simulates the wave interference. This technique produces what is known as moire shadow contouring or moire topography.

Instead of using actual wave interference, a grid pattern or grating is projected onto the surface of the object to be measured (see Figure 25). The grid is a pattern of equal width straight lines which is projected at right angles to the direction of viewing or photography. The periodic grating is illuminated with a collimated (parallel) beam of light, casting a shadow of the grating onto the object. This is geometrically equivalent to intersecting the 3-D surface with a series of parallel planes (Lovesey, 1974). This produces constant height contours of equal separation on the object which are then used to determine the shape of the surface (Moore & Truax, 1979). The image of the grating becomes deformed by the contours on the surface of the object. The deformation in the projected pattern is analyzed to determine the range information or surface profile (Srinivasan, Liu, & Halioua, 1984).

The deformed pattern is the moire pattern from which measurements can be taken of the fringe position. The deformed pattern is measured against the pattern that the grid lines make when they are projected onto a flat surface. These measurements, along with the vertical

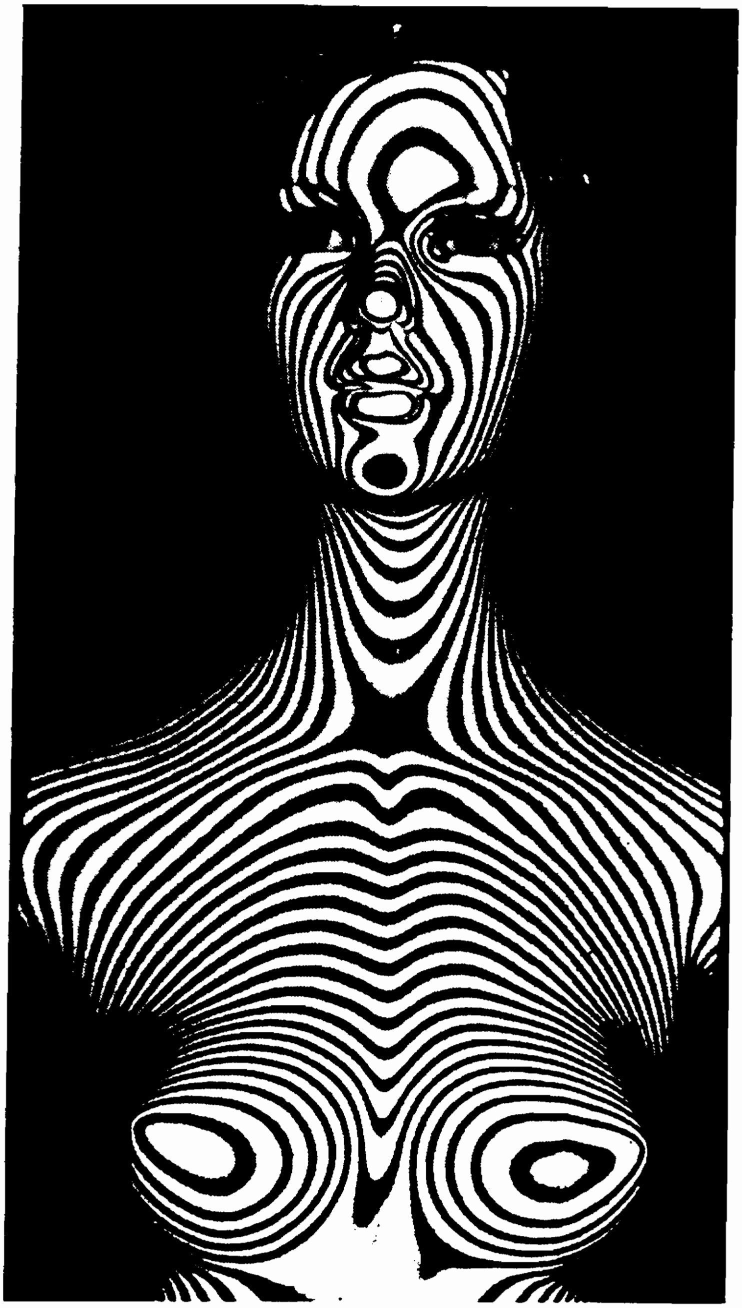

Figure 25. Contour lines formed on a manikin by moire projection

Note. From "Moire topography" by H. Takasaki, Biostereometrics '74, American Society for Photogrammetry, p. 596. Fig. 6.

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separation of the fringes, can be used to determine the shape of the object surface. Every point along these lines can be characterized by a unique phase value by using interferometric phase measuring algorithms. "By measuring this phase accurately using phase modulation methods and by determining points on the reference plane and the object having identical phases, it is shown that the object height [or range] can be computed" (Srinivasan, Liu and, Halioua, 1985, p. 185).

The moire fringe measurement method was made even more accurate by use of a phase shift. "By oscillating the phase of the moire pattern a small amount, it is possible to determine the phase of the pattern to a much higher degree of accuracy than is possible in a static system" (measuring from only one fringe projection) (Moore & Truax, 1979, p. 91). In the first system one set of calculations could be performed on the fringe pattern. By using a phase shift with this method a second set of calculations can be obtained. The fringes are measured first in one position and then shifted a known amount and measured again. When the phase is shifted by one third and the calculations done a second time, the resulting measurements have a high resolution (Srinivasan, et al., 1985). For this reason, a high degree of accuracy is attained using this method (G. Indebetouw, personal communication, April, 1989). The data derived from the moire fringe method of measurement can be used to produce a topographical map of the surface contours of the object and also to provide cross-sectional information about the object.

When black and white lines are used for analysis in this method it is sometimes difficult to differentiate lines in areas of high curvature and contour density. By using colored lines instead, individual contours can be easily traced with accuracy of less than one millimeter.

The measuring accuracy of this method is reported to be 2π/100 for human body forms. The accuracy as tested by Lovesey (1974) on a flat object was found to be .66 mm. The resolution of this method can be very high but only at the expense of reduced range (Balasubramian, 1976).

"Most of the direct optical contouring schemes are applicable to only small objects since all of them require artificial illumination, coherent or incoherent of the object scene" (Balasubramian, 1976). Originally, the main source of error in using the moire fringe method of measurement was that unless the projector and camera were placed a long way from the subject (preferably at infinity) the contour spacing varied with the distance from the projector. Therefore, the nose would produce a larger image than the ear. This problem was eliminated, however, by using telecentric lenses. The telecentric lens records only parallel rays from the subject (rather than the cone of rays used when the subject is recorded in perspective). The diameter of the telecentric lens, however, limits the size of the object to be measured. Therefore, when measuring large objects (such as the human body) the telecentric lens should not be used. Instead, a lens should be used with known internal geometry so that divergence errors may be calculated (Lovesey, 1974).

Another problem associated with using this method is that since the coordinates of the contour lines are determined relatively instead of absolutely, it is not easy to connect two or more topographies taken from different views. Moire techniques are also very alignment critical and sensitive to disturbance. They require extensive digital image processing which makes them costly (Kuhlman, 1988).

Although the surface contours generated by regular moire methods are easily interpreted by a human they are somewhat more complicated for computer analysis. The geometrical analysis of the deformed grating which requires fringe peak determination are computationally slow, and result in low accuracy (Srinivasan, et al., 1984). The methods of phase modulation interferometry, which are well known for their accuracy, were used in a method by Srinivasan, Liu & Halioua (1984) first with collimated laser light (1984) and then with a source of white light (1985). The surface shape of the object is converted into a phase distribution as in interferometry, and digital phase measuring techniques, well known for their accuracy, are used for the analysis (Halioua, Liu, Chin, & Bowins, 1988). "In the four-shift algorithm, four interferograms are obtained by shifting the grating by increments of one quarter period, and the unknown phase function [is] retrieved independently from the background and contrast parameters" (Halioua, et al., 1988).

The use of white light makes the system more practical and capable of handling large objects. The phase-measuring is automatically performed by computer. Using this system a complete 3-D profile can be generated in a matter of seconds. The accuracy of this method is of the order of 0.1 mm.

Time of Flight

Another approach to calculating range information is by time of flight calculations. This method determines the range distance by calculating the time needed for a projected energy pulse (sound, microwave, light, laser) to travel from the transmitter to the object being measured and back (Posdamer et al., 1982). This type of system is referred to as echometric.

Short, Mutch, Anderson, & Grover, (1974) developed a method to record body shape using the echo time of airborne ultrasound pulses impinging on the human body from a rotating ultrasonic camera. The scanning is done in a series of horizontal rings. The data are stored on a paper tape through a computer. The data are then manipulated to provide a graphic display of the surface contours by cross-sectional outputs of each horizontal scan. These are used to calculate total body surface area and volume. The Short et al. system was limited to use with a maximum distance between subject and camera of three feet (approx. 275 cm.). At this distance 50 data points can be read every second. The entire scan is made in six minutes.

This method, as it was used in a later study by Anderson, Vincent & Marks (1978) is capable of recording a camera-to-subject distance between 15-75 cm. Circular scans are made at every 6 cm. of height. Each scan records 250 measurements (one every 1.44 degrees). The beginning and end of each scan is indicated by a synchronisation pulse. The output of the camera and synchronisation pulses are recorded on an FM instrumentation recorder. A graphics procedure produces cross section outlines. Trigonometric routines are used to calculate the circumference and area of each cross section.

Because this approach is based upon the reflection of the energy pulse from the surface of the object it works best with solid objects which reflect energy well. "The human skin behaves very differently to the various forms of energy which strike its surface" (Short, et al., 1974, p. 584). Ultrasonic radiation is reflected by the surface of the skin while very high frequency electromagnetic radiation is absorbed. The absorbtion of any energy generates heat and may cause tissue or bone damage (Short et al., 1974).

Because of the complex shape of the body multiple reflections occur frequently which may completely cancel the signal at some frequencies and produce an error. The accuracy and resoltuion of this method is affected by the distortion and dispersion of the ultrasound beam due to the surface properties of the skin, particularly where its contour is irregular or sharply angles. Errors of up to 5% may also occur in the distance measurements because of deviations in clock rate and tape replay speed.

Summary

Developments in techniques of analyzing the human body have been far-reaching. Objective information about the form of the body was at first limited to only two-dimensional data. This information was derived from actual measurements taken directly on the body. Two-dimensional data, however, provide a very limited picture in describing the shape of the body.

Earliest three-dimensional measuring methods required physically contacting the body with the measuring instrument. Although these methods are slow and tedious to use three-dimensional information can be obtained in this manner. However, the time required to complete a full set of measurements to describe a body is such that problems occur due to subject fatigue. When the subject being measured is fatigued the position and stance of the body changes enough to produce inaccuracies in the data.

As non-contact methods of analysis were developed more information became available which describes the body form. The first descriptions were derived from photographs and were subjective analyses of total body form. Further developments of photographic methods provided objective three-dimensional data which more completely specified body shape. The development of other non-contact methods which are based on the projection of lasers, light waves, grids, and energy pulses are even more sophisticated and provide a highly accurate and comprehensive description of the body. Most non-contact methods are much quicker to use than contact methods which eliminates the problem of subject fatigue.

By interfacing a computer with a non-contact measuring system the three-dimensional data can be analyzed in a number of ways, i.e., horizontal or vertical cross sections, or angles between points. This type of analysis is required in order to make a comparison between the contours of different bodies. The technology exists to record accurate three-dimensional data describing the body surface. It appears that stereophotography, moire topography, or phase-measuring profilometry are the most developed in terms of their potential for accurately measuring the human body. Even these methods would need further development to obtain a completely comprehensive set of data to describe the three-dimensional body. The areas under the arms and between the legs are not described by stereophotographic methods, moire topography, or by phase-measuring profilometry. Developers of the optical methods acknowledge the need to perfect an edge-matching component so that two 180° views can be accurately combined. Whether stereophotographic methods have perfected this process is not clear.

DEVELOPMENT OF A METHOD

Methods which are currently available to measure the body form in three dimensions are not yet fully developed. In order to derive the type of information which would completely describe all areas of the body further developments are necessary. Most available three-dimensional measuring methods require specialized equipment which is usually quite expensive. Also, personnel must be specially-trained to operate the equipment and analyze the results. Because these factors could be potential problems a new method was sought to accomplish this goal.

The goal of this research is to identify a means of defining and specifying an average three-dimensional form from any given sample of human bodies. This research will be conducted by the following steps: 1) determine the criteria which govern the solution of the problem; 2) develop and pretest a method based on established criteria and; 3) report findings.

Determine the Criteria which Govern the Solution of the Problem

The problem is to define a method of determining an average three-dimensional form from a sample of human bodies. To that end, a discussion of the requirements imposed by this endeavor is in order.

The requirements for a method must include the provision of three-dimensional data. Two-dimensional information is not sufficient to describe the shape, form, posture, and location of contours as is required. Therefore, <u>three-dimensional information must be derived from</u>

the method.

In order to accurately represent the human body with a set of data it is necessary that actual human bodies be used in obtaining the data. This necessitates the participation of human subjects in this research. There are legal guidelines based on safety and humanitarianism regarding the use of human subjects for research. Therefore, since this study requires the use of human participants, it is necessary that the method pose no health hazards or other risks to any person involved.

Any analysis of body size and shape requires the use of some type of recording system through which the data can be expressed in an understandable manner (Burwell, 1977). The three-dimensional size and shape of the body can be expressed by a three-dimensional model, a two-dimensional graphic display (such as a contour map) or numerically by a set of x, y, and z coordinates. In fact, graphic descriptions of the body are often converted into quantifiable data (Whittle, et al, 1977; Herron, 1972, Cornelis, et al., 1978; Srinivasan et al., 1984) and the data, in turn, can be converted into a graphic description. "In practice, three-dimensional digital coordinates (Cartesian or other systems) are so much more versatile, parsimonious and compatible with the ubiquitous digital computer..."[than a contour map] (Herron, 1972, p. 80). Digital coordinates lend themselves to analysis and are more specific in relaying information to others. Therefore, the method should provide quantifiable data about the body surface in the form of three-dimensional digital coordinates.

The three-dimensional data must be an accurate representation of the body surface. To cross check the accuracy of the data derived from a three-dimensional method it can be compared to anthropometric measurements. The three-dimensional data can also be used as a "map" to compare against the actual body that it represents. In this way, the data that are provided by the measuring method can be used to locate the corresponding points on the body which was measured.

It is imperative that the data which are collected are as accurate a representation of the size, shape, and form of the standing, static human body as possible. Therefore, the subject will be required to remain as motionless as possible for the period during which information is being gathered. Even slight movements will alter the data. Because of this restriction on time, <u>the method used to collect data should not be such that the time required to capture the three-dimensional data requires the subjects to stand motionless to the point of fatigue.</u> Subject fatigue would lead to changes in body stance and inconsistent data.

Since the data base which is obtained from this research is to be used to derive an <u>average</u> of a particular group, a large number of bodies should be used for the analysis. The size of the sample for this research should be determined by the size of the population, the variance in the population, and the amount of error in the sample which is tolerable. The larger the population which is to be represented by the average that is to be determined by this method, the greater the sample size needed (Cole, 1980).

Each surface point on the body will be located by an x, y, and z coordinate. The data set to describe the surface of a single body will therefore be quite large. Since the method is to be used with a large sample of bodies, the total data set will be of cumbersome and unwieldy proportions. There, it will be necessary to use a method capable of handling a large amount of data. This will require the use of a computer.

In order to calculate an average from a sample group it will be necessary to have a record of the 3-D data that are collected so that they may be analyzed and compared with the data describing other bodies. Therefore, the data which are collected must be stored in some manner and be available for editing and comparison.

Since the method will be used with large samples of bodies the collection and entry of data should not be overly time-intensive. If a measuring method required a large amount of time to collect and store data for a single body it would not be manageable to use with a large sample.

It is questionable whether human bodies are perfectly symmetrical or not. Most people at least believe that one side of their body is larger than the other (Annis, 1978). Symmetrical differences may not be related to size differences, however, as much as to differences in location of contours.

Laubach and McConville (1967) surveyed a group of young male subjects by taking 21 paired measurements to determine right/left asymmetry. Their results show statistically significant differences in eight of the 21 measurements. Of these eight measurements, five are measurements taken on the arms. It is probable that these differences are due to the handedness of the subjects although this information is not available. In twelve measurements the mean difference is less than one mm. Giddings (1982), in her study of anthropometric differences in black and white males, found that human bodies are rarely, if ever symmetrical. Burwell & Dangerfield (1977) conducted a study of asymmetry of the body and found that symmetrical differences occur not only in scoliotic patients but in "normal" persons as well.

These differences are in anthropometric measurements and therefore reflect only actual dimensional measurements. Additional differences such as variations in contour placement would be evident if a body were measured three-dimensionally. These differences have not been documented. This research will be conducted so that asymmetry can be documented.

Whether or not human bodies are perfectly symmetrical it is necessary that manikins are. If the data provided by this measuring method are to be used for the production of a manikin it would be necessary that symmetry was achieved along the sagittal plane. Because asymetrical differences in a body would be unique to that particular body it would not be possible to find a consistent pattern of right side/left side differences. Moreover, these differences could not be duplicated within one standard form. The best approach to this problem would be to determine an average right side and an average left side of the bodies surveyed. These two average sides could then be averaged again to find the half-body most representative of the entire sample group.

This averaging of separate halves of the body will be easier to accomplish by dividing the body (represented by a set of data) along the sagittal plane. <u>A measurement method which is capable of separating a</u>

three-dimensional object along a given plane will facilitate this process.

In order to attain symmetry along the sagittal plane it is necessary to reverse the data which represents one half of the body to describe the other half. In this way, each half is identical to the other in shape and location of contour. By creating a mirror image of a set of data along a given plane symmetry will be achieved.

A review of the criteria which govern the development and testing of a three-dimensional measuring method are that in using the method:

- participants will not be subjected to any health hazards/risks
- quantifiable three-dimensional data about the body surface is provided
- accurate data are provided
- subjects are not involved to the point of fatigue
- a large amount of data must be handled by the system
- information is stored within the system
- data may be manipulated
- collection and entry of data are not time intensive
- a 3-D object can be divided along a given plane
- mirror-imaging along a given plane is possible

Development and Pretest of a New Method Based on Established Criteria

Based upon the criteria which were determined in the preceding section a method of measuring the human body in three dimensions was developed and tested. The first requirement was to find a system with the capacity to analyze objects in three dimensions that could be adapted to this research with the human body.

The field of engineering is a forerunner in developing methods which are capable of analyzing an object in three dimensions. Most applications of these developments concern the design and/or manufacturing of objects. Even though these systems have not been used to specify the three-dimensional qualities of the human body it appeared that the capability was there to do so.

One of the oldest systems of this type was developed by Lockheed Corporation in the 1960s. It was first used as a tool in the design and manufacture of aircraft (Myklebust, Pennington, Dhande, 1989). The Computer-graphics Augmented Design And Manufacturing (CADAM) system is an an interactive graphics system. Drawings can be created and stored in a central design data base.

The CADAM system may be used in either a 2-D or 3-D mode. CADAM Access is a software which interfaces with a data base. It contains two components: 1) geometry interface and; 2) interactive user exit (IUE). The Geometry Interface component allows the user to interface geometry programs with a CADAM model.

The capabilities of this system appeared to be such that a three-dimensional measurement system could be built around it. It seemed possible to use the CADAM system to construct a three-dimensional object from two-dimensional views of the object.

In devising a three-dimensional measuring system which could be used with the CADAM system, photographs were used to capture two-dimensional views of the body. These photographs were then digitized to derive the two-dimensional points which defined the silhouette of the body. The points which defined the silhouette were used as a spline in the CADAM system. After the two-dimensional silhouettes had been defined they were written into a CADAM program which transformed all points into three dimensions. The CADAM system could then be used to analyze the three-dimensional structure.

This method was to be tested first on a manikin. The manikin was used before a human body because it was easier to work with than a human body for several reasons: 1) it did not change its stance once it had been put into place; 2) there were no arms to obstruct the view of the body, 3) it did not change in shape or dimensions between the time the information was gathered and when it could be verified and; 4) the time it took to work out problems with the camera set up did in itself lead to subject fatigue. After using the manikin to determine that the method could be used to give a clear description of the "body" surface it would then be tested with a small sample of actual human bodies.

Photography

The first step in this method was to obtain photographs of the body which could be used to define the two-dimensional body silhouette. A 35 mm camera with a telephoto lens was placed on a tripod at a distance of 30' from the manikin to minimize the distortion due to parallax (see Figure 26). Kodak Ektachrome 160 ASA slide film was used with an F stop of 4.5 and a shutter speed of 1/60 second.

The center front and side seam line of the manikin was marked with black twill tape so that it would be more visible through the camera lens. The manikin was then placed on a round 18" turntable which was

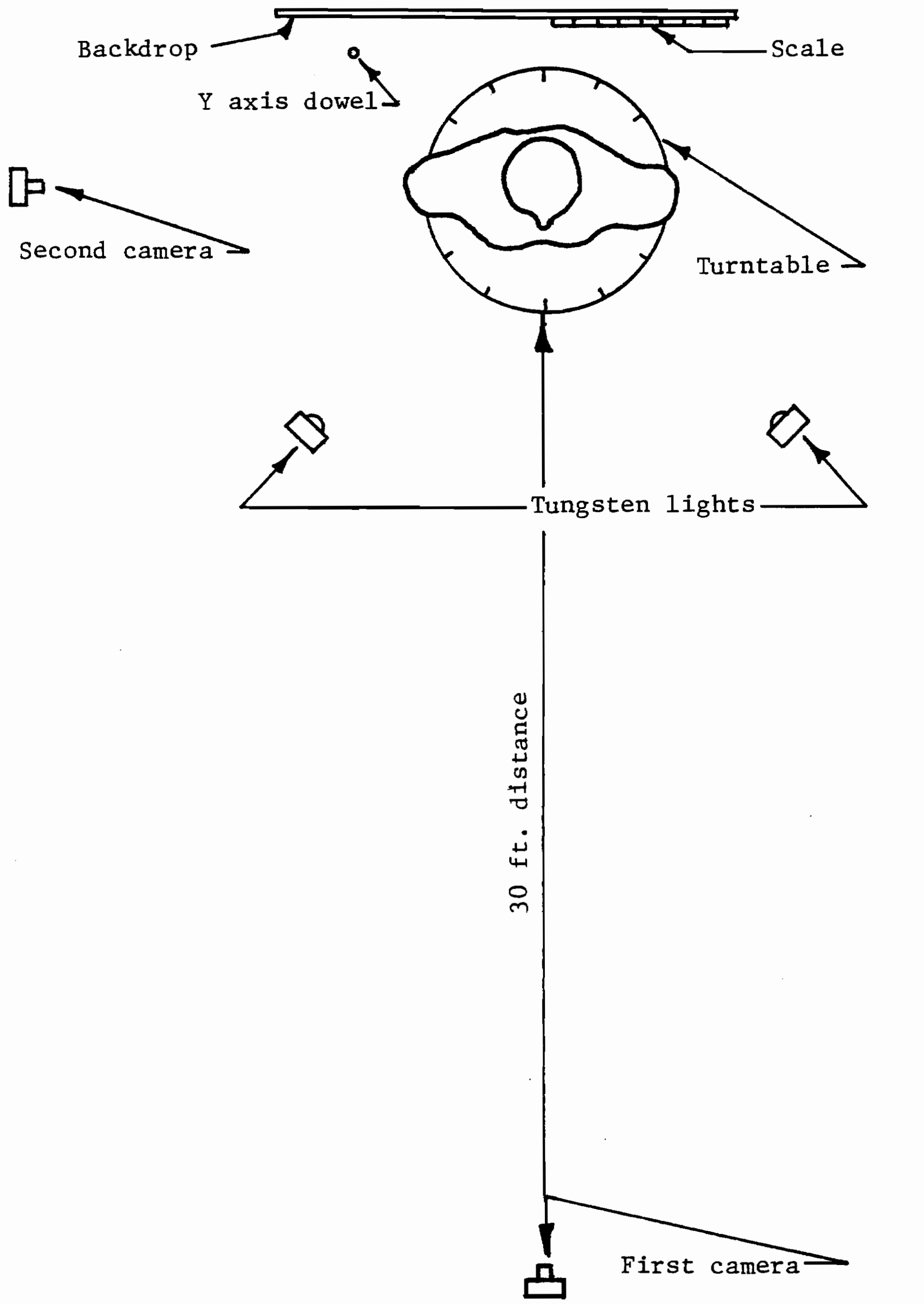

Figure 26. Photography setup used with CADAM/ACSYNT method

marked into 22-1/2° segments on the outer perimeter. The turntable was constructed with a locking device composed of a pin which fit vertically through a hole drilled through the turntable at each 22-1/2° segment line to keep the turntable from shifting. The dress form manikin was removed from its wheel base stand and set on the turntable directly on the wire framework bottom. The removal of the manikin from its stand was necessary in order for it to fit and rotate within the confines of the turntable.

A dark-colored fabric was hung flat against a wall behind the manikin to provide as much contrast as possible for determining the silhouette of the light-colored manikin when the slide was projected on the digitizer screen.

A 1/2" wooden dowel served as the y axis reference line. Small tacks were pushed into either side of the dowel near one end. A cord was wrapped and tied around these extended tacks and then securely taped to the ceiling so that the dowel hung to the side of the manikin where it was still in the photograph. A dot was marked on the dowel so that it was visible in the photographs and served as the 0,0 reference mark for setting the Cartesian Coordinate system. An actual size reference scale was also included in the photographs. This consisted of a black line marked into one inch increments which was drawn on a white poster board.

The manikin was illuminated by two tungsten lights mounted on floor stands which were placed approximately four feet in front of the manikin and off to either side at approximately a 45 degree angle. The exact placement of the lights was chosen by determining the location where the least amount of shadow was shed along the silhouette line of the manikin in a position where the light stands did not interfere with the photograph.

The camera was levelled so that the y axis (dowel) was in parallel to the vertical cross hairs of the camera lens. The manikin was then brought to this same vertical orientation by placing wooden shims between the wire frame bottom and the turntable until the center front line of the manikin was in line with the vertical cross hairs of the camera lens.

The telephoto lens was adjusted so that the manikin filled as much of the photograph as possible while still clearly showing the reference scale and the Y-axis dowel.

Eight photographs were taken using this set up, with the manikin being rotated 22-1/2° between each exposure. These eight rotations took the manikin from the position of center front facing directly toward the camera to center back facing directly toward the camera and provided a complete 360° view of the body silhouettes.

Digitizing

After the slides had been processed they were loaded into a Kodak Ektagraphic III carousel projector which projected the image onto the screen of a Numonics Model 1224 electronic digital analyzer. A sheet of clear acrylic was marked with horizontal lines every 1/2" and attached to the front of the viewing screen. The slide projector was positioned so that the image of the manikin filled as much of the screen as possible while still retaining a sharp contrast along the silhouette lines. It was also necessary that the 0,0 reference dot was visible.

The digitizer was interfaced with an IBM personal computer so that the digitized points which represented the silhouette of the manikin could be stored on a floppy disk. A program written in Basic (Appendix A) read each point from the digitizer, rounded it to the four nearest decimal places (1/10,000) and stored it on the disk.

By measuring the reference scale which appeared in the photograph the actual scale size could be calculated. The digitizer was then set to this scale. For each of the eight photographs the points were digitized where each horizontal line on the clear acrylic intersected the outer edge of the manikin. The 0,0 reference point was reset for each photograph using the dot which was visible on the y axis. The right side of the manikin was digitized first beginning at the neck and proceeding to the bottom. The right side of the first photograph was labelled "View 1." The left side of the first photograph was labelled "View 9" to correspond with the plane represented by this set of points. Each consecutive photograph was labelled accordingly. In this way 16 splines were digitized from the eight photographs. When the set of eight photographs had been digitized this data were saved as a separate file representing one body or manikin.

Entering the Data

A special Fortran program (Appendix B) was written for this project on the mainframe computer. A printed copy of the data was then used to enter the data into the Fortran program. The original plan had been to input the data directly from the floppy disk into the program. However, the way in which the program was written required the x and y components of each datum point to be entered separately. The program was written to interface the digitized data with the CADAM program in the Department of Mechanical Engineering. The x value for each digitized point had to be entered separately with the first x value (the point where the first horizontal line crossed the silhouette) for the first view being entered first, then the first x value for the second view and so on. After all the x values had been entered the y values were entered in the same way. The data at this point were rounded to the nearest one hundredth.

In order to establish the same horizontal planes passing through the 3-D object in each view the data were analyzed before entering them into the Fortran program. The y value points were listed for each view at each of the horizontal intersections that had been digitized. These usually varied a maximum of plus or minus two tenths from the most frequently occurring value. The most frequently occurring value was consistently used for each y value at each of the horizontal planes. The data entered into the Fortran program were the same for the first y value in each of the eight views, the second y value in each of the eight views and so forth. After the entire set of two-dimensional data had been keyed into the Fortran program the file was ready to be compiled.

The CADAM Process

The Fortan program was written so that the geometry of the points in relation to each other could be used to calculate the third dimension for each of the points in the file (the z value). The 22½° angle between each view was used in calculating the transformation of each point from its 2-D location to its 3-D location. After each point was located in three-dimensional space the program used the new 3-D coordinates to build vertical splines between each set of points. In this manner each of the eight views of the body was transformed into a vertical spline which indicated the silhouette of the body in that view.

After a set of eight vertical splines was formed, the points were joined horizontally at each y point that had been entered. The combination of the vertical and horizontal splines formed a wire frame model. This wire frame model would then be used to build surface patches between the splines.

During this part of the process there was an obvious aberration in the way in which the splines were joined together. There were some points on the 3-D model which did not correspond to the shape of the manikin at all. The neck location was the most obvious problem because the neck is at more of a forward angle than the rest of the body. Therefore, as the photographs were taken at every 22½° degree rotation the points which outlined the silhouette of the upper extremity of the neck "tracked" in an elliptical pattern. This same problem was probably occurring elsewhere in the model as well although in a less obvious way. It was first thought that this problem was due to noise in the data from slight shifts in the positioning of the "body" during photography.

To eliminate most of the noise from the data a new photographic procedure was devised which would center the manikin more precisely. The photographic procedure was the same as that previously described with this addition. Once the manikin was perfectly aligned and centered from the front another camera was set up on a tripod at 90° so that the side seam line of the manikin was aligned with the vertical cross hairs of the camera lens. The manikin was then rotated on the turntable 90°. The alignment of the second camera was then checked to see if the center front line of the manikin was centered and aligned with the vertical cross hair lines of the camera lens. If this alignment was not exact the manikin was shifted on the turntable until the alignment appeared the same when viewed through either camera after a rotation of 90°.

The data from the new set of photographs showed some of the same problems when compiled into a wire frame model. It was also at this point that plans were made to mathematically transform the points on the neck (to theta = 0). Each point would be calculated so that its location could be determined before the rotation was made.

During the planning of how the wire frame model would be used to compare several bodies another problem came to light. It appeared that the variations in body contours for any particular area of the body could best be compared by overlaying cross sections. In this way the waist or any other specific area of many bodies could be compared.

With the CADAM program, however, it was only possible to take cross sections of the model at the specific location where the horizontal planes (defined by the lines on the acrylic sheet) intersected the vertical splines. This limitation would be a serious detriment when attempting to compare very specific body areas. For instance, if the waist areas of two bodies were to be compared and the exact spline/horizontal plane intersection did not occur at the waist, it would be impossible to compare these cross sections.

ACSYNT

The faculty of the Mechanical Engineering Department had a solution to this problem. The staff of the CAD Lab had recently completed a contract for NASA to write a program for 3-D modelling. The program was to be used for the construction of space craft. However, the program was written with three-dimensional modelling capabilities that included a specific component to enable the user to take cross sections at any location desired. This program was made accessible for use in this research.

The NASA program developed at Virginia Polytechnic Institute and State University is called ACSYNT. The original program was over 150,000 lines long and had to be greatly modified to use for 3-D body modelling. After this modification was complete the data were entered into this new program (Appendix C) and compiled. The same type of distortion appeared in the 3-D model. Mathematical transformations were then written into the program in an attempt to keep the points tracking in a circular pattern. The new results formed a perfect circular cross-section that did not represent the body at all.

Summary

The problems with the distortion in the body form were very likely the result of several factors. The major disadvantage to obtaining data this way is the inability to define a central axis which can be consistently located in each photograph. If the points from each view are not linked to a common axis there is no way of accurately joining one set of points to the next. Also, as the "body" was rotated between photographs slight shifts may have occurred in its placement on the turntable. Even a very small shift would result in noise in the data.

Further steps need to be taken toward establishing a centrally located axis or reference system in order for this method to be developed. If the points which define a body silhouette in several views can be accurately related, this may be a feasible method to develop for use.

DISCUSSION AND RECOMMENDATIONS

Two-dimensional anthropometric measurements were once the only type of body specification available for quantifiably describing the size and shape of the human form. Measurement methods have since become more refined and sophisticated. Today, much more information than body dimensions alone can be deduced about the body surface. It is now possible to record body specifications in three dimensions. The precise size, shape, and form of the human body can be described indicating individual posture and the placement of every contour. The ability to describe a body by such comprehensive specificiations is the result of steady technological progress. New methods of quantifiably analyzing and measuring the body reflect this progress in their increased precision and accuracy.

The purpose of this research was to identify a means of defining and specifying an average three-dimensional form from any given sample of human bodies. In order to do this, existing methods were identified, the criteria were determined which govern the solution of the problem, and a new method based on the established criteria was developed and tested.

The body can be analyzed in three dimensions using existing measurement methods. These methods still require further development before a complete and detailed 3-D form of the body can be derived. For the most part, these methods require sophisticated equipment and/or trained personnel that were not immediately available for use with the project. It was hoped that a comparable method could be developed using the facilities which were available.

It requires substantially more information to describe a three-dimensional object than it does to describe a two-dimensional object. Points which are located in two dimensional space can be precisely described by two numerical values. Points located in three dimensions are not fully described even with three numerical values. If the points define a surface such as the human body each point must also be defined by the multi-directional curvature of the surface upon which it is located. Unless the matrix of points used to describe an object is infinitely dense the surface between the points is subject to assumptions and interpolation.

A method of obtaining three-dimensional measurements was developed and tested using the equipment and facilities available at Virginia Polytechnic Institute and State University. After reviewing other three-dimensional measuring methods and considering the needs of this project the procedural components of a measuring method were developed. The procedures used with the CADAM system involved obtaining two-dimensional information from photographs of the body; converting the information into data; inputting the data into a computer design system with three-dimensional capabilities; converting the data into a mathematically-described three-dimensional form and; analyzing the three-dimensional form. A three-dimensional picture of several bodies would provide a clearer idea of the type and magnitude of differences which occur between bodies.

The CADAM system is usually used by inputting two-dimensional information describing a three-dimensional object for which the surface geometry is already known. This study defined the edges of two-dimensional slices of a three-dimensional object and used the CADAM system to piece these together. The human body is unlike an object with well-defined sides and sharp edges. These pieces have no easily identifiable common axis. Therefore, when linking the edges of each slice together an assumption is made about the centrality of the axis. If the body were a perfect cylinder this would not be a problem. The central axis would then be centrally located at each cross-section taken.

Since the initial part of this research was not successful the development of a means of analyzing the differences in contours between several bodies could not be attempted. This type of analysis should have been possible by using cross sections of the same area of the body for a number of bodies.

Although a three-dimensional form of the body was not accurately derived by the method developed in this research, other valuable information was discovered. A system was established for presenting and photographing the body so that information could be obtained about body shape. A method was developed for transforming two-dimensional points into three-dimensional points and, for joining points into splines which define the silhouettes of the body by using a specially-written CADAM program. These components of this research project should be useful in further developing a three-dimensional measuring method.

The CADAM method works on the same basic principles as those used in stereophotography. However, in stereophotography a single point on the body can be located in two different photographs. This allows triangulation calculations to be used in determining the exact location of that point in three-dimensional space. When using the CADAM method a point on the body is located only once as it becomes a part of the silhouette. In this way, each silhouette is made up of a set of mutually exclusive points.

The points that form the silhouettes are joined together to form both vertical and horizontal splines. However, these splines are made up of points that have not been located in three-dimensional space and this allows room for error.

One possible way to eliminate this problem may be to identify specific points on the body. Regular body landmarks could be used or a type of grid could be drawn or projected onto the surface of the skin. In this way, specific points could be identified in more than one photograph and this information could be used to more precisely locate each point in relation to the other points. Once a body is specified with three-dimensional data the means of analyzing differences between various bodies can continue.

Until the problems with the CADAM method can be resolved it may be more expeditious to look into using one of the other types of three-dimensional measurement. Since the accuracy of these methods has already been tested it would involve much less testing before the actual project work could be completed. Based on the funds which are available for conducting this research and the time frame for its completion another method may be a more viable alternative.

It would appear that the most developed methods available at this time are 1) stereophotography; 2) rasterstereophotography; 3) laser projection or; 4) projection moire. Both stereophotography and raster-stereophotography require equipment which is quite sophisticated and expensive. Personnel to use the equipment are highly trained. These factors may prevent these methods from being feasible alternatives.

Many new developments are taking place in the field of laser projection systems. The intensity of the laser beams used is being reduced to a safe level. However, these systems still require a high level of stability in order for the laser to track in an accurate pattern. The time required to complete a scan of the total body may also be prohibitive especially for use with a large sample.

Some systems which are based on projection moire provide accurate and detailed information rapidly and at a low cost. New developments of moire-based systems are based on the use of equipment which is easy to obtain. These systems should be investigated further as a means of establishing a three-dimensional data base for a large sample.

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APPENDICES

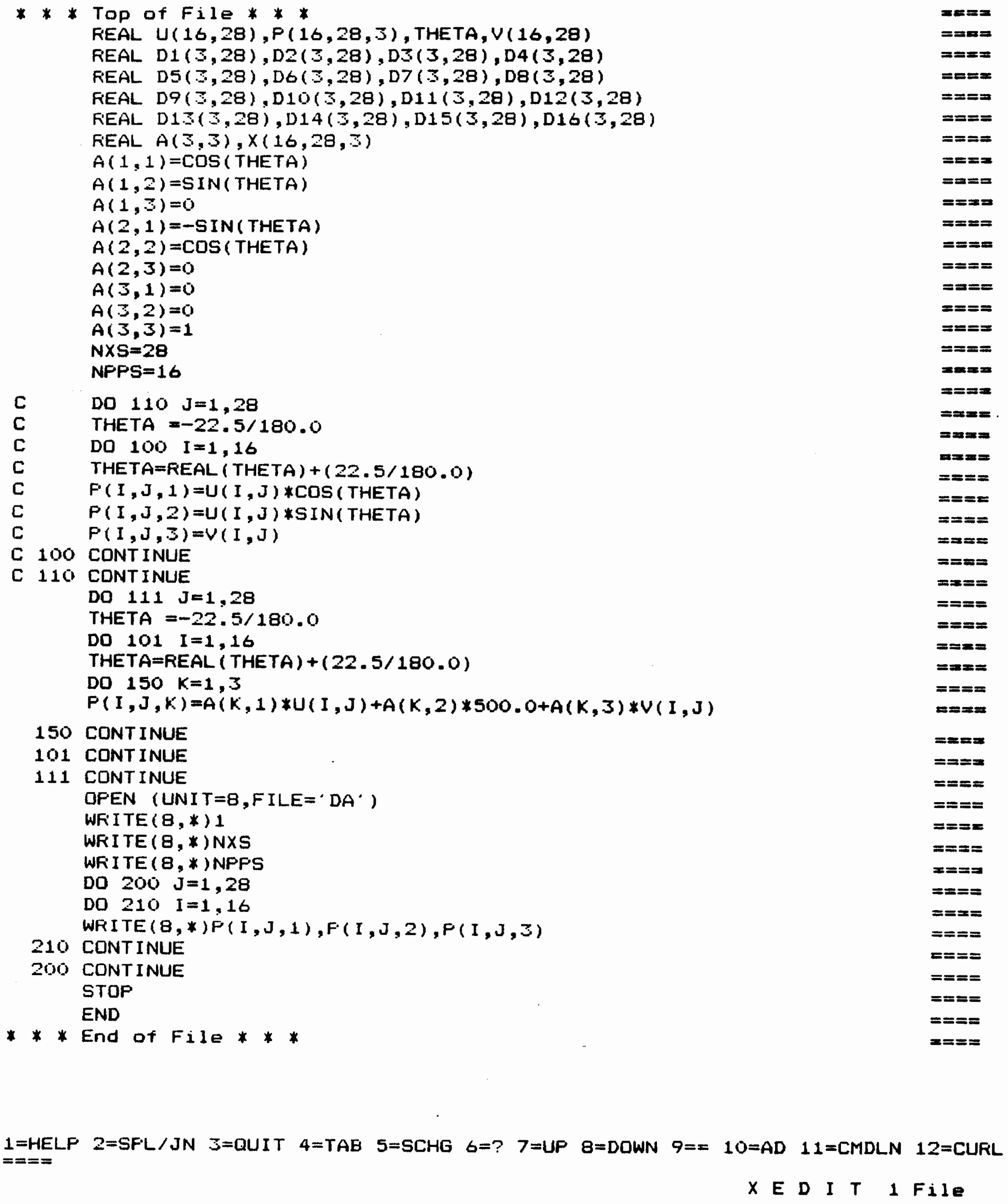
Appendix A

BASIC Program to Store Digitized Data

```
10 CLS
20 PRINT "  WHAT IS MODEL NUMBER?     "
30 PRINT:PRINT "be sure your printer is on" :PRINT
40 INPUT "(or type quit to quit now)    ",M$
50 IF (M$="QUIT" OR M$="quit") THEN END
60 OPEN M$  FOR APPEND AS #1
70 OPEN "com1:9600,e,7,,cs,ds,cd" AS #2
80 CLS:INPUT "ENTER 'QUIT' OR VIEW NUMBER:  ",V$
90 IF (V$="quit" OR V$="QUIT") THEN END
100 PRINT:INPUT "OTHER ID OR COMMENTS?    ",C$
110 PRINT #1, M$,V$,C$:REM LPRINT M$,V$,C$
120 F$=" "
130 WHILE F$<>"last" AND F$<>"LAST"
140 CLS
150 PRINT "WAITING FOR INPUT"
160 LINE INPUT #2,L$
170 PRINT:INPUT "enter any flag now or 'last' to end this view   " ,F$
180 PRINT #1,L$,F$
190 REM LPRINT L$,F$
200 WEND
210 REM LPRINT:LPRINT
220 GOTO 80
230 CLOSE
240 END
```

Appendix B

Fortran Program to Compile Two-Dimensional Data through CADAM into Three Dimensional Splines



```
* * * Top of File * * *                                                ====
      REAL U(16,28),P(16,28,3),THETA,V(16,28)                           ====
      REAL D1(3,28),D2(3,28),D3(3,28),D4(3,28)                          ====
      REAL D5(3,28),D6(3,28),D7(3,28),D8(3,28)                          ====
      REAL D9(3,28),D10(3,28),D11(3,28),D12(3,28)                       ====
      REAL D13(3,28),D14(3,28),D15(3,28),D16(3,28)                      ====
      REAL A(3,3),X(16,28,3)                                            ====
      A(1,1)=COS(THETA)                                                 ====
      A(1,2)=SIN(THETA)                                                 ====
      A(1,3)=0                                                          ====
      A(2,1)=-SIN(THETA)                                                ====
      A(2,2)=COS(THETA)                                                 ====
      A(2,3)=0                                                          ====
      A(3,1)=0                                                          ====
      A(3,2)=0                                                          ====
      A(3,3)=1                                                          ====
      NXS=28                                                            ====
      NPPS=16                                                           ====
                                                                        ====
C     DO 110 J=1,28                                                     ====
C     THETA =-22.5/180.0                                                ====
C     DO 100 I=1,16                                                     ====
C     THETA=REAL(THETA)+(22.5/180.0)                                    ====
C     P(I,J,1)=U(I,J)*COS(THETA)                                        ====
C     P(I,J,2)=U(I,J)*SIN(THETA)                                        ====
C     P(I,J,3)=V(I,J)                                                   ====
C 100 CONTINUE                                                          ====
C 110 CONTINUE                                                          ====
      DO 111 J=1,28                                                     ====
      THETA =-22.5/180.0                                                ====
      DO 101 I=1,16                                                     ====
      THETA=REAL(THETA)+(22.5/180.0)                                    ====
      DO 150 K=1,3                                                      ====
      P(I,J,K)=A(K,1)*U(I,J)+A(K,2)*500.0+A(K,3)*V(I,J)                 ====
  150 CONTINUE                                                          ====
  101 CONTINUE                                                          ====
  111 CONTINUE                                                          ====
      OPEN (UNIT=8,FILE='DA')                                           ====
      WRITE(8,*)1                                                       ====
      WRITE(8,*)NXS                                                     ====
      WRITE(8,*)NPPS                                                    ====
      DO 200 J=1,28                                                     ====
      DO 210 I=1,16                                                     ====
      WRITE(8,*)P(I,J,1),P(I,J,2),P(I,J,3)                              ====
  210 CONTINUE                                                          ====
  200 CONTINUE                                                          ====
      STOP                                                              ====
      END                                                               ====
* * * End of File * * *                                                 ====



1=HELP 2=SPL/JN 3=QUIT 4=TAB 5=SCHG 6=? 7=UP 8=DOWN 9== 10=AD 11=CMDLN 12=CURL
====
                                                          X E D I T  1 File
```

```
BIG2     FORTRAN  A1  V 80  Trunc=72 Size=1352 Line=0 Col=1 Alt=0

* * * Top of File * * *                                           ====
      CHARACTER DRAWID*20,USERID*8,GROUP*4,IDVU*4                 ====
      REAL U(16,31),P(16,31,3),THETA,V(16,31)                     ====
      REAL XYZ(3),XVCTR(3),YVCTR(3),ZVCTR(3)                      ====
      REAL G(3,31),CAD(31),DU1(31)/31*0.0/                        ====
      REAL DU2(31)/31*0.0/,DU3(31)/31*0.0/                        ====
      REAL DU4(16)/16*0.0/,DU5(16)/16*0.0/                        ====
      REAL DU6(16)/16*0.0/,G2(3,16)                               ====
      REAL D1(3,31),D2(3,31),D3(3,31),D4(3,31)                    ====
      REAL D5(3,31),D6(3,31),D7(3,31),D8(3,31)                    ====
      REAL D9(3,31),D10(3,31),D11(3,31),D12(3,31)                 ====
      REAL D13(3,31),D14(3,31),D15(3,31),D16(3,31)                ====
      REAL D21(3,16),D22(3,16),D23(3,16),D24(3,16)                ====
      REAL D25(3,16),D26(3,16),D27(3,16),D28(3,16)                ====
      REAL D29(3,16),D30(3,16),D31(3,16),D32(3,16)                ====
      REAL D33(3,16),D34(3,16),D35(3,16),D36(3,16)                ====
      REAL D37(3,31),D38(3,31),D39(3,31),D40(3,31)                ====
      REAL D41(3,16),D42(3,16),D43(3,16),D44(3,16)                ====
      REAL D45(3,16),D46(3,16),D47(3,16),D48(3,16)                ====
      REAL D45(3,16),D46(3,16),D47(3,16),D48(3,16)                ====
      REAL D49(3,16),D50(3,16),D51(3,16)                          ====
      DATA DRAWID/'MANUQ1              '/,USERID/'WENDER  '/      ====
      DATA GROUP/'GENL'/,IDVU/'  V1'/                             ====
      DATA XYZ/0.0,0.0,0.0/,XVCTR/1.0,0.0,0.0/                    ====
      DATA YVCTR/0.0,1.0,0.0/,ZVCTR/0.0,0.0,1.0/                  ====
      IOPT=1                                                      ====
      ICODE=1                                                     ====
      NMPTS=31                                                    ====
      NDIMS=3                                                     ====
      IEND=0                                                      ====
      NDSPL=2                                                     ====
      NPTS=16                                                     ====
      U(1,1)=1.34                                                 ====
      U(2,1)=1.06                                                 ====
      U(3,1)=0.17                                                 ====
      U(4,1)=0.00                                                 ====
      U(5,1)=0.09                                                 ====
      U(6.1)=0.11                                                 ====
  77  CONTINUE                                                    ====
  76  CONTINUE                                                    ====
                                                                  ====
      WRITE(5,*)'BEGINNING OF CAD SUBROUTINES'                    ====
      CALL CADST(DRAWID,USERID,GROUP)                             ====
      WRITE(5,*)'CALLING BEGVU'                                   ====
      CALL BEGVU(IOPT,IDVU,XYZ,XVCTR,YVCTR,ZVCTR,*400)            ====
      WRITE(5,*)'BEGINNING OF VERTICAL SPLINE SUBROUTINES'        ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D1,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE1,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE1'                            ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D2,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE2,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE2'                            ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D3,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE3,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE3'                            ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D4,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE4,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE4'                            ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D5,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE5,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE5'                            ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D6,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE6,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE6'                            ====
      CALL SPLINE(NMPTS,NDIMS,IEND,D7,G,CAD,DU1,DU2,DU3,*1001)    ====
      CALL NAME(SPLINE7,*2001)                                    ====
      WRITE(5,*) 'NO ERROR IN SPLINE7'                            ====
```

```
CALL SPLINE(NMPTS,NDIMS,IEND,D8,G,CAD,DU1,DU2,DU3,*1001)        ====
CALL NAME(SPLINE8,*2001)                                         ====
WRITE(5,*) 'NO ERROR IN SPLINE8'                                 ====
CALL SPLINE(NMPTS,NDIMS,IEND,D9,G,CAD,DU1,DU2,DU3,*1001)        ====
CALL NAME(SPLINE9,*2001)                                         ====
WRITE(5,*) 'NO ERROR IN SPLINE9'                                 ====
CALL SPLINE(NMPTS,NDIMS,IEND,D10,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE10,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE10'                                ====
CALL SPLINE(NMPTS,NDIMS,IEND,D11,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE11,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE11'                                ====
CALL SPLINE(NMPTS,NDIMS,IEND,D12,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE12,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE12'                                ====
CALL SPLINE(NMPTS,NDIMS,IEND,D13,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE13,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE13'                                ====
CALL SPLINE(NMPTS,NDIMS,IEND,D14,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE14,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE14'                                ====
CALL SPLINE(NMPTS,NDIMS,IEND,D15,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE15,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE15'                                ====
CALL SPLINE(NMPTS,NDIMS,IEND,D16,G,CAD,DU1,DU2,DU3,*1001)       ====
CALL NAME(SPLINE16,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE16'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D21,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE21,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE21'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D22,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE22,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE22'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D23,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE23,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE23'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D24,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE24,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE24'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D25,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE25,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE25'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D26,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE26,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE26'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D27,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE27,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE27'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D28,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE28,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE28'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D29,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE29,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE29'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D30,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE30,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE30'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D31,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE31,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE31'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D32,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE32,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE32'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D33,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE33,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE33'                                ====
CALL SPLINE(NPTS,NDIMS,IEND,D34,G2,CAD,DU4,DU5,DU6,*1001)       ====
CALL NAME(SPLINE34,*2001)                                        ====
WRITE(5,*) 'NO ERROR IN SPLINE34'                                ====
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CALL SPLINE(NPTS,NDIMS,IEND,D35,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE35,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE35'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D36,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE36,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE36'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D37,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE37,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE37'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D38,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE38,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE38'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D39,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE39,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE39'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D40,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE40,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE40'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D41,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE41,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE41'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D42,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE42,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE42'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D43,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE43,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE43'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D44,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE44,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE44'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D45,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE45,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE45'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D46,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE46.*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE46'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D47,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE47,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE47'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D48,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE48,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE48'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D49,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE49,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE49'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D50,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE50,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE50'                                   ====
CALL SPLINE(NPTS,NDIMS,IEND,D51,G2,CAD,DU4,DU5,DU6,*1001)           ====
CALL NAME(SPLINE51,*2001)                                           ====
WRITE(5,*) 'NO ERROR IN SPLINE51'                                   ====
WRITE(5,*) 'BEGINNING OF RULED SURFACE SUBROUTINES'                 ====
CALL SRFRUL(SPLINE1,SPLINE2,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 1'                           ====
CALL SRFRUL(SPLINE2,SPLINE3,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 2'                           ====
CALL SRFRUL(SPLINE3,SPLINE4,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 3'                           ====
CALL SRFRUL(SPLINE4,SPLINE5,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 4'                           ====
CALL SRFRUL(SPLINE5,SPLINE6,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 5'                           ====
CALL SRFRUL(SPLINE6,SPLINE7,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 6'                           ====
CALL SRFRUL(SPLINE7,SPLINE8,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 7'                           ====
CALL SRFRUL(SPLINE8,SPLINE9,NDSPL,*1003)                            ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 8'                           ====
CALL SRFRUL(SPLINE9,SPLINE10,NDSPL,*1003)                           ====
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WRITE(5,*) ' NO ERROR IN RULED SURFACE 9'                                ====
CALL SRFRUL(SPLINE10,SPLINE11,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 10'                               ====
CALL SRFRUL(SPLINE11,SPLINE12,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 11'                               ====
CALL SRFRUL(SPLINE12,SPLINE13,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 12'                               ====
CALL SRFRUL(SPLINE13,SPLINE14,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 13'                               ====
CALL SRFRUL(SPLINE14,SPLINE15,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 14'                               ====
CALL SRFRUL(SPLINE15,SPLINE16,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 15'                               ====
CALL SRFRUL(SPLINE16,SPLINE1,NDSPL,*1003)                                ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 16'                               ====
CALL SRFRUL(SPLINE21,SPLINE22,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 21'                               ====
CALL SRFRUL(SPLINE22,SPLINE23,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 22'                               ====
CALL SRFRUL(SPLINE23,SPLINE24,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 23'                               ====
CALL SRFRUL(SPLINE24,SPLINE25,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 24'                               ====
CALL SRFRUL(SPLINE25,SPLINE26,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 25'                               ====
CALL SRFRUL(SPLINE26,SPLINE27,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 26'                               ====
CALL SRFRUL(SPLINE27,SPLINE28,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 27'                               ====
CALL SRFRUL(SPLINE28,SPLINE29,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 28'                               ====
CALL SRFRUL(SPLINE29,SPLINE30,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 29'                               ====
CALL SRFRUL(SPLINE30,SPLINE31,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 30'                               ====
CALL SRFRUL(SPLINE31,SPLINE32,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 31'                               ====
CALL SRFRUL(SPLINE32,SPLINE33,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 32'                               ====
CALL SRFRUL(SPLINE33,SPLINE34,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 33'                               ====
CALL SRFRUL(SPLINE34,SPLINE35,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 34'                               ====
CALL SRFRUL(SPLINE35,SPLINE36,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 35'                               ====
CALL SRFRUL(SPLINE36,SPLINE37,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 36'                               ====
CALL SRFRUL(SPLINE37,SPLINE38,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 37'                               ====
CALL SRFRUL(SPLINE38,SPLINE39,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 38'                               ====
CALL SRFRUL(SPLINE39,SPLINE40,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 29'                               ====
CALL SRFRUL(SPLINE40,SPLINE41,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 40'                               ====
CALL SRFRUL(SPLINE41,SPLINE42,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 41'                               ====
CALL SRFRUL(SPLINE42,SPLINE43,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 42'                               ====
CALL SRFRUL(SPLINE43,SPLINE44,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 43'                               ====
CALL SRFRUL(SPLINE44,SPLINE45,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 44'                               ====
CALL SRFRUL(SPLINE45,SPLINE46,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 45'                               ====
CALL SRFRUL(SPLINE46,SPLINE47,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 46'                               ====
CALL SRFRUL(SPLINE47,SPLINE48,NDSPL,*1003)                               ====
WRITE(5,*) ' NO ERROR IN RULED SURFACE 47'                               ====
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      CALL SRFRUL(SPLINE48,SPLINE49,NDSPL,*1003)                          ====
      WRITE(5,*) ' NO ERROR IN RULED SURFACE 48'                          ====
      CALL SRFRUL(SPLINE49,SPLINE50,NDSPL,*1003)                          ====
      WRITE(5,*) ' NO ERROR IN RULED SURFACE 49'                          ====
      CALL SRFRUL(SPLINE50,SPLINE51,NDSPL,*1003)                          ====
      WRITE(5,*) ' NO ERROR IN RULED SURFACE 50'                          ====
      WRITE(5,*)'CALLING ENDVU'                                           ====
      CALL ENDVU(*1900)                                                   ====
      GOTO 2000                                                           ====
  400 WRITE(5,*)'ERROR IN BEGVU'                                          ====
      GOTO 2000                                                           ====
  500 WRITE(5,*)'ERROR IN POINT'                                          ====
      GOTO 2000                                                           ====
 1001 WRITE(5,*)'ERROR IN SPLINE'                                         ====
      GOTO 2000                                                           ====
 2001 WRITE(5,*)'ERROR IN SPLINE NAME'                                    ====
      GOTO 2000                                                           ====
 1003 WRITE(5,*)'ERROR IN SURFACE'                                        ====
      GOTO 2000                                                           ====
 1900 WRITE(5,*)'ERROR IN ENDVU'                                          ====
      GOTO 2000                                                           ====
 2000 IOPT=2                                                              ====
      NOGOOD=0                                                            ====
      WRITE(5,*)'CALLING CADFIL SUBROUTINE'                               ====
      CALL CADFIL(IOPT,NOGOOD,IDUMMY)                                     ====
      IF(NOGOOD.NE.1)THEN                                                 ====
      WRITE(5,1905)NOGOOD                                                 ====
 1905 FORMAT(2X,'ERROR IN CADFIL',2X,'NOGOOD=',I2)                        ====
      ENDIF                                                               ====
 1906 STOP                                                                ====
      END                                                                 ====
                                                                          ====
```

VITA

Kaye Ann Wender was born March 23, 1952 in Iron Mountain, Michigan. She graduated from Kingsford High School in 1970. She intermittently attended Northern Michigan University in Marquette, Michigan and Montana State University in Bozeman, Montana over a period of ten years before receiving a Bachelor of Science degree in Home Economics, Family Life Sciences & Child Development in June, 1981.

Ms. Wender again returned to school in December, 1987 at Virginia Polytechnic Institute and State University and received a Master of Science degree in Clothing & Textiles in January, 1990. While at VPI & SU she was employed as a Graduate Research Assistant in the Apparel Research & Development Lab under the direction of Dr. Joann Boles. She is currently employed in the Pattern/Engineering Department of a garment manufacturer.