COMPUTER GENERATION OF GRAPHIC THREE-DIMENSIONAL REPRESENTATION OF FACIAL GROWTH IN OLIVE BABOONS

(PAPIO CYNOCHEPALUS ANUBIS)

A Thesis
by
KATHLEEN LOWRY EAVES

Submitted to the Graduate College of Texas A&M University in partial fulfillment of the requirements for the degree of MASTER OF ARTS

December 1979

Major Subject: Anthropology
COMPUTER GENERATION OF GRAPHIC THREE-DIMENSIONAL REPRESENTATION OF FACIAL GROWTH IN OLIVE BABOONS

(PAPO CYNOCHEPHALUS ANUBIS)

A Thesis
by
KATHLEEN LOWRY EAVES

Approved as to style and content by:

[Signatures]

(Chairman of Committee)

(Member)

(Member)

(Member)

(Member)

(Head of Department)

December 1979
ABSTRACT

Computer Generation of Graphic Three-dimensional Representation of Facial Growth in Olive Baboons
(Papio cynocephalus anubis). (December 1979)
Kathleen Lowry Eaves, B.A., Texas A&M University
Chairman of Advisory Committee: Dr. Norman Thomas

A methodology for the use of a digital computer for generation of graphic representation of three-dimensional changes in the cranium and face is described. Data from the Oyen-Walker stereometric craniostat are presented in tabular form and in two graphic forms: outline plots of individual skulls and plots of the location of a single anatomical point on a series of skulls. The programs were developed using data from a cross-sectional group of olive baboons (Papio cynocephalus anubis). The problem of establishing a consistent reference plane and zero point is discussed. Possible future uses of the methodology by clinicians and by anthropologists are described.
DEDICATION

We have learned to cherish the company of those who can make us laugh, who can forgive us our shortcomings, who can restore to us or evoke in us a feeling of purpose in the face of absurdity. These are the people we choose for our clans.

Jane Howard, Families

To the clan which developed during this project:
Dr. Warren Heffington, Dr. Ordean Oyen, Dr. Cynthia Gillette, Dr. Robert Rice, Dr. Bruce Dickson, Dr. Norman Thomas, Dr. Robert Godsey, the Pests - Ted, Jenny, Debbie, John, Pat, Pete, Leonard, Grace, and Yale, Sande Nissen, John Purcell, my kith and kin, especially my parents Charles and Evelyn Lowry, the Martins - John, Isobel, Philippa, and Gregory, and to Steve, my husband, who was going through the same thing at the same time but who always knew when I needed a back rub,
this work is gratefully and affectionately dedicated.
ACKNOWLEDGEMENTS

This work is an outgrowth of Dr. Ordean J. Oyen's doctoral research at the University of Minnesota. Many thanks are extended to him for allowing me to use the original data from his dissertation. This project was inspired by Dr. Warren Heffington and the advertisements he wrote promoting the course Engineering Design Graphics 408. Dr. Heffington directed the development of the programs described herein. Many thanks are extended to him for the hours he spent explaining computer graphics to me. Computer funds were provided by the Department of Engineering Design Graphics and the College of Liberal Arts, Texas A&M University. Photo work was done by John Purcell. In addition to being sounding boards for the problems which developed during the course of this work, John and Isobel Martin provided the coffee after many long nights at the Teague Computing Center. Many thanks are also due to Stephen Eaves who helped me punch in 3154 data points and who gave me valuable assistance during the preparation of this thesis.
TABLE OF CONTENTS

INTRODUCTION ......................................................... 1
LITERATURE REVIEW .................................................. 2
    Racial Classification ............................................ 2
    Growth Studies of Human and Non-human Primates ... 3
    Anthropometric Tools and Techniques ...................... 4
METHODOLOGY .......................................................... 8
    Introduction ..................................................... 8
    Data Collection ................................................ 9
    Data Entry ...................................................... 11
    Data Conversion ............................................... 11
    Error Diagnosis ............................................... 12
    Data Plotting .................................................. 12
    Technical Information ......................................... 36
RESULTS AND DISCUSSION ............................................. 38
    Future Research and Applications .......................... 42
SUMMARY ............................................................... 46
LITERATURE CITED ................................................... 47
APPENDIX I ............................................................. 50
APPENDIX II ........................................................... 51
VITA ................................................................. 56
<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Oyen-Walker Stereoplotting Craniostat</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>An Adult Male Baboon Shown in norma lateralis</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>An Infant Male Baboon Shown in norma lateralis</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>A Computer-generated Outline Plot of Male Baboons</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>An Adult Female Baboon Shown in norma lateralis</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>An Infant Female Baboon Shown in norma lateralis</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>A Computer-generated Outline Plot of Female Baboons</td>
<td>23</td>
</tr>
<tr>
<td>8</td>
<td>A Lateral X-ray of a Female Baboon</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>Movement of Alveolare in Profile View (norma lateralis)</td>
<td>26</td>
</tr>
<tr>
<td>10</td>
<td>Movement of Alveolare in Top View</td>
<td>27</td>
</tr>
<tr>
<td>11</td>
<td>Movement of Alveolare in Front View (norma frontalis)</td>
<td>28</td>
</tr>
<tr>
<td>12</td>
<td>Movement of Alveolare in Isometric Projection</td>
<td>29</td>
</tr>
<tr>
<td>13</td>
<td>A Baboon Skull in norma lateralis</td>
<td>31</td>
</tr>
<tr>
<td>14</td>
<td>A Baboon Skull in norma frontalis</td>
<td>33</td>
</tr>
<tr>
<td>15</td>
<td>A Baboon Skull in Isometric Projection</td>
<td>35</td>
</tr>
</tbody>
</table>
INTRODUCTION

Physical anthropology is the study of human variation and evolution (Washburn, '62, p.76). Traditionally, physical anthropology has been based on the study of skulls of living and fossil primates and hominids (Washburn, '62, p.83). One method of understanding variation is to analyze growth and development.

Most previous growth and development studies only analyzed growth in two dimensions (Herron, '72). Oyen ('74) has shown the usefulness of viewing growth in three dimensions. However, as Herron ('72) pointed out, collection of three-dimensional data has required use of sophisticated camera equipment or has involved extrapolation of three-dimensional data from two-dimensional techniques such as x-ray methods. The Oyen-Walker stereoplotting craniostat is an instrument which yields three-dimensional data yet can be moved easily (Oyen and Walker, '77). Since craniostat data are in spherical coordinates and few techniques are discussed in the anthropological literature for treatment of spherical coordinates, this project was developed. It was assumed that computer programs could be written which would generate graphic representations of craniostat data, allowing the data to be compared to data gathered by conventional two-dimensional studies and allowing easy visualization of patterns of change and growth. The successful accomplishment of these ends I believe is borne out in the following sections.

This thesis follows the citation style of the American Journal of Physical Anthropology.
LITERATURE REVIEW

The conceptual roots of this project lie in three areas of physical anthropology: racial classification, growth studies of human and non-human primates, and development of anthropometric tools and techniques.

Racial Classification

In 1738, Carolus Linnaeus listed four varieties of man in his book *Systema Naturae* (Malefijt, '74, p.258). One hundred and twenty years later, Johann Blumenbach classified humans on the basis of head shape (Montagu, '64). Studies of head shape were given further impetus by the publication in 1835 of Franz Gall's work on phrenology (Malefijt, '74, p. 260). In his book, Gall maintained that mental capabilities were centered in the brain. He claimed that different parts of the brain have different functions and that the size of each part is a reflection of the development of the function performed by that part. Consequently, he claimed, the bumps on the skull were a reflection of the development of the brain and mental functions and would accurately indicate the personality and mental ability of the individual (Malefijt, '74, p. 260).

Many studies subsequent to the work by Blumenbach and Gall were attempts to determine and quantify racial differences in mental capabilities. In America, Samuel Morton published *Crania Americana* (1839) in which he classified four racial types on the basis of thirteen cranial measurements. George Combe quantified cranial differences between the races using a craniometer he developed (Hoyme, '53, p. 413).

At the turn of the century, some of the studies of
racial differences included multi-generational studies. Franz Boas published one of the first comparisons of first and second generation immigrants to the United States in 1911. It was entitled *Changes in Bodily Form of Descendants of Immigrants* (Boas, '11) and dealt primarily with changes in head shape between generations of immigrants to the United States. In his report, Boas compared differences in the cephalic index, a common measure of head shape which is based on the ratio of head length to head width. One of Boas' conclusions was that descendants of immigrants to the United States differ from their forebearers in body shape and size because the cultural environments in which they matured were different (Boas, '11). Boas' conclusions as to the importance of cultural environment have been supported by later work such as that by Shapiro ('39) which confirmed that physical differences between first and second generation immigrants to the United States were primarily due to cultural environmental differences.

Growth Studies of Human and Non-human Primates

 Craniofacial growth studies by physical anthropologists deal with growth in both human and non-human primates. Schultz ('24), Zuckerman ('26, '28), and Krogman ('30) were among the first to chronicle facial growth in non-human primates. Early studies such as these were primarily descriptive efforts which used two-dimensional or linear measurements, including total head length, total head width, and other distances between two anatomical points. This method of describing crania by a series of linear measurements is still in use today (e.g., Walker, '67; Krogman, '69).

In 1951, Sherwood Washburn suggested a shift in emphasis
in physical anthropology from description to explanation. He stated, "If traditional physical anthropology was 80 percent measurement and 20 percent concerned with heredity, process, and anatomy, in the new physical anthropology the proportions may be approximately reversed" ('51, p.303). He defined the new physical anthropology as "primarily an area of interest, the desire to understand the process of primate evolution and human variation by the most efficient techniques available" ('51, p.298).

Anthropometric Tools and Techniques

Washburn described the "common core" of the old physical anthropology as "measurement of external form with calipers" ('51, p.298). Combe, Morton, and Boas used calipers in their studies of human skulls and heads (Hoyme, '53, pp.413-416; Boas, '11).

Another method of obtaining linear measurements is by use of x-ray films. Standard anatomical points known as landmarks are identified on the x-ray film and a ruler or calipers are used to measure the distance between the two points. Angles between three points can also be determined (Baumrind and Frantz, '71a, '71b).

Many errors can be made in a growth study based on data derived from x-ray films (Baumrind and Frantz, '71a, '71b; Baumrind, Miller, and Molthen, '76). Some of these include inconsistent identification of landmarks, errors in alignment of the head with the x-ray film causing projection error, and inconsistent superimposition of films (Baumrind, Miller, and Molthen, '76). Any of these errors can cause the researcher to see a growth pattern which may not be the same as reality. Baumrind and Frantz ('71a, '71b) quantified these errors and concluded, "Our current measurement instrument, the angular
headfilm measurement, is in most cases too inaccurate to differentiate all but the grossest changes" (71b, p.516).

Various techniques have been developed to minimize these errors. G. F. Walker ('67) discussed the use of an electronic digitizer to generate x-ray data more accurately. Nevertheless, points must still be visually located before the corresponding coordinates are digitized. Walker ('67) also discussed developments in totally automated systems. None of the systems described by Walker had been tested for use with x-ray films at the time of his article. Dana, Eisenfeld, and Mishelevich ('79) wrote a computer program which can be used with point coordinates obtained from x-ray films by an electronic digitizer such as the one described by Walker ('67). The program will calculate linear and angular measurements from the two-dimensional coordinates of anatomical points.

Another method for the study of growth developed for use with standard head x-ray films is the application of Fourier analysis to description of irregular surfaces such as the outline of the skull. Lestrel and Moore ('78) painted the midline of the cranial base of fetal Macaca nemistrina skulls with barium sulfate, an x-ray opaque material, then x-rayed the heads. The outline of the cranial base was an irregular curve which was then characterized by Fourier analysis, a complex mathematical methodology (Lestrel and Moore, '78).

Three-dimensional techniques have been developed in an attempt to describe the human body more completely (Herron, '72, p.80). Because biological forms are irregular, two-dimensional measurements are limited in their ability to describe the forms (Herron, '72, p.80).

One such method is stereophotogrammetry (Herron, '72).
This technique involves the use of two cameras with overlapping fields of view. The object to be measured is placed away from the cameras and photographed. The resulting photographs are then viewed through a stereoplotting instrument and the three-dimensional coordinates of a point on the object are recorded. Using this technique, analysis of the data can be done by a digital computer (Herron, '72). Although stereophotogrammetry was developed in 1832, Herron ('72) claimed that it has not been widely accepted as a technique for growth studies due to computational difficulties and general lack of availability of specialized equipment (p.90).

Another technique developed for obtaining three-dimensional data is laser holography. Young and Altschuler ('77) discussed application of laser holography to dentistry. One possible use is generation of data for contour maps of surfaces such as the crowns of molars. Holographic technique is too complex for summary here (see Young and Altschuler, '77 for description of methodology), but application of holography to growth studies would require the use of both a laser and a digital computer.

An instrument used for obtaining three-dimensional data from skulls is the Oyen-Walker stereoplotting craniostat (Oyen and Walker, '77). The craniostat gives the three-dimensional coordinates of a point on a skull in spherical dimensions, radial distance, azimuth angle, and elevation angle, all of which are referenced to an arbitrary zero point. Spherical coordinates can be plotted on graph paper known as a Wulff net. Also, standard linear measurements can be calculated from the coordinates of two points. A physical description of the craniostat will be supplied in the dis-
cussion of the methodology.

As Herron ('72) stated, "In practice, three-dimensional digital coordinates (Cartesian or other systems) are so much more versatile, parsimonious and compatible with the ubiquitous digital computer (compared to contour maps)" (p. 80). Oyen and Walker ('77) claimed, "With ... the development of programs written for stereometric data, the study of growth and form will have yet another analytic tool that may lead to further understanding of basic problems and processes" (p. 181).

This project was a response to the need for analysis of stereometric data with computer techniques. Programs were developed which convert spherical coordinate data to rectangular data and to plot the data in two graphic forms as well as to print tables of converted data. One graphic form is an outline picture of a single skull; the other is the location of a single anatomical point on many different skulls. These programs increase the usefulness of craniostat data by graphically presenting the data in a form which can be compared to x-ray films or which shows growth patterns.
METHODOLOGY

Introduction

The purpose of this thesis is to develop a methodology using a digital computer to generate graphic representations of growth of skulls in three dimensions using data such as that obtained from the Oyen-Walker stereoplotting craniostat (Oyen and Walker, '77). Growth is represented by graphing changes in either shape or size of skulls through time. However, the data used in this study were derived from a cross-sectional collection of skulls, and the plots generated from these data do not show growth in its strictest meaning.

The Oyen-Walker stereoplotting craniostat measures the location of an anatomical point in spherical coordinates. Previously, the published suggestions for data handling consisted of two ideas: plotting of craniometric data on spherical coordinate graph paper known as a Wulff net, or calculation of standard linear measurements (Oyen, '74; Oyen and Walker, '77). A Wulff net plot shows the angular location of points, azimuth and elevation, but radial distance cannot be directly graphed (Oyen, '74). The equation for calculating the linear distance between two points is a standard mathematical formula

\[ D = \sqrt{R_1^2 + R_2^2 - 2R_1R_2(\cos A_1 \cos A_2 \cos (E_1 - E_2) + \sin A_1 A_2)} \]  

where \( D \) is the linear distance between the two points and \( R_1, A_1, E_1 \), and \( R_2, A_2, E_2 \) are the radial distance, azimuth angle, and elevation angle of the first and second points, respectively (Oyen, '74).

This project extends the possible uses for craniostat data by generating tables of rectangular coordinates along
with two forms of graphic output: outline pictures of a single skull, and plots of positions of a single point on skulls of different ages.

Data Collection

Data used in this project were collected using the Oyen-Walker stereoplotting craniostat. The craniostat consists of an open rotatable circle, an arc attached at right angles to the circle, and a radially mounted movable needle attached to the arc. The arc and the surface surrounding the circle are calibrated in degrees; the needle is calibrated in millimeters to the center of the sphere (Figure 1). The needle mount moves along the arc and indicates the degrees of elevation; the arc rotates around the circle and indicates the degrees of azimuth (Oyen and Walker, '77).

Measurement of the location of points on a skull is accomplished by centering the skull inside the craniostat, rotating the arc around the circle, and adjusting the needle both on the arc and in the mount until the needle makes contact with the anatomical point to be located. The values of the three spherical coordinates, radial distance (R), azimuth angle (A), and elevation angle (E), are read directly off the craniostat (Oyen, '74; Oyen and Walker, '77).

Fifty-three anatomical points on skulls from seventy-four olive baboons (Papio cynocephalus anubis) were measured by Dr. Ordean J. Oyen ('74). The data were derived from a cross-sectional collection of skulls that range in age from infants with not fully erupted deciduous dentition (milk teeth) to fully adult as evidenced by dentition. Only limited information about individual ages is available. A full description of the specimens can be found in Oyen ('74).
Figure 1  The Oyen-Walker Stereoplotting Craniostat

A. Rotating circle, azimuth indicator
B. Arc, elevation indicator
C. Needle mount, calibrated in millimeters
D. Needle, radial distance indicator
E. Center point needle

Redrawn from Oyen and Walker, ('77). Used by permission of the authors.
Data Entry

The data entered into the program consisted of six numbers for each point location measured. The first three numbers were the radial distance \( R \) in millimeters, the azimuth angle \( A \) in degrees, and the elevation angle \( E \) in degrees. The next two numbers were identification numbers: the first identifying the specimen; the second identifying the anatomical point. The last number was a pen control number for use with the plotter.

Data Conversion

The spherical coordinate data were converted to rectangular coordinate by the computer. During the conversion, the angle values for azimuth and elevation were converted from degrees to radians, necessary because the AMDAHL 470 V/6 computer used would not correctly calculate the trigonometric functions used in later equations if the angle values were not in radians. Conversion from spherical to rectangular coordinates was accomplished by means of the following formulae:

\[
\begin{align*}
  X &= R \cos(A) \cos(E) / 25.4, \\
  Y &= R \sin(E) / 25.4, \quad \text{and} \\
  Z &= R \sin(A) \cos(E) / 25.4,
\end{align*}
\]

where \( X, Y, \) and \( Z \) are the new spherical coordinates and \( R, A, \) and \( E \) are the spherical coordinates as previously defined. The constant 25.4 is the conversion factor from millimeters to inches, necessary because the line printer is designed to work in inches. The new rectangular coordinates and the corresponding identification numbers were stored in the com-
ter's memory for later use. If tabular output of the data is
desired, it is printed at this step in the program.

Error Diagnosis

As the values for the spherical coordinates of each
data point were entered into the computer, each number was
checked by the computer to determine whether it fell within
an acceptable range of values. If not, the point was not
entered into memory and an error message was printed saying
an erroneous point had been encountered. Thus, if the ex-
treme values for azimuth angle A were zero and 200 degrees,
the acceptable range might be entered as zero to 220 de-
grees. Then, if a value of 260 degrees was erroneously en-
tered for A, the diagnostic section of the program would
print an error message. This section could not find all
errors, but could locate numbers which were either too large
or too small due to faulty data transcription.

Data Plotting

Two types of plots were generated by the programs. The
first is an outline drawing of an individual skull, rotated
to any viewing angle. The second is a plot of the location
of a single anatomical point on any or all of the skulls
in the data set. This plot can also be rotated to any view-
ing angle.

Either one of these plots is initiated by sorting the
data according to identification number before plotting.
For an outline of a skull, the data are sorted by specimen
number. All data with the desired specimen number are plot-
ted; all others are ignored. Similarly, the second kind of
plot is drawn after points are sorted by anatomical point
identification number. Those points having the desired num-
ber are plotted; all others are ignored.

Another feature of the program is its ability to superimpose plots. By inserting two or three lines into the program, the user can cause subsequent plots to be drawn superimposed on previous plots. The following series of figures compares photographs with the computer plots. All skulls are in norma lateralis. Figures 2 and 3 show photographs of an adult male baboon and an infant male baboon, respectively. The same skulls are outline plotted in Figure 4. Because only the outlines are plotted and the plots are superimposed, the changes in the shape of the skulls are easily visualized. Figures 5 and 6 are photographs of an adult female baboon and an infant female baboon, respectively. Figure 7 is the outline plot of the same skulls. For comparison, Figure 8 shows a lateral x-ray of an adult female baboon. The outline plot and x-ray show similar information. However, while the data that generated Figure 7 can be used to draw the skulls from any viewing angle, the x-ray film cannot be rotated to show the skull from any viewing angle other than the one recorded on the film.

Figures 9, 10, 11, and 12 show the position of the anatomical point alveolare, the point on the skull directly between the two central incisors at the inferior alveolar margin, from different viewing angles. In Figure 9, the skull is shown in right profile view (norma lateralis). The apparent movement of alveolare to the right indicates that the muzzle of the olive baboon lengthens with age. Figure 10 shows a top view of alveolare. This is equivalent to looking down on the top of the skull. Again, the nose faces to the right. The movement of alveolare shows that the muzzle grows longer with age when viewed from the top. Figure
Figure 2. An Adult Male Baboon Shown in norma lateralis.
Figure 3. An Infant Male Baboon shown in norma lateralis.
Figure 4. A Computer-generated Outline Plot of Male Baboons.
Figure 5. An Adult Female Baboon Shown in *norma lateralis*.
Figure 6. An Infant Female Baboon Shown in *norma* lateralis.
Figure 7. A Computer-generated Outline Plot of Female Baboons.
Figure 8. A Lateral X-Ray of a Female Baboon.
Figure 9. Movement of alveolare in profile view (norma lateralis).
Figure 11. Movement of alveolare in front view (norma frontalis).
Figure 12. Movement of alveolarc in isometric projection.
Figure 13. A Baboon Skull in norma lateralis.
Figure 14. A Baboon Skull in norma frontalis.
Figure 15. A Baboon Skull in Isometric Projection.
ll shows alveolare from the front (norma frontalis). As might be predicted from the previous plots, there is no apparent movement of alveolare when viewed from this angle. Figure 12 shows an isometric projection of alveolare. This projection shows all three coordinate axes at once, each 120 degrees from the others. This projection can give an appearance of three dimensions to the drawings which is missing from the other projection angles. In this projection, the nose of the skull is facing down and to the right. Movement can be seen to occur in a fairly straight line away from the left side of the drawing.

Figures 13, 14, and 15 show a skull in norma lateralis, norma frontalis, and a view approximating isometric projection, respectively. These photographs are included for comparison with the computer plots. Figure 15 shows how an isometric projection can give a greater effect of three dimensions than can the other two views.

Technical Information

The programs were written in a standard scientific programming language, FORTRAN IV, and WATFIV was the compiler used (Cress, Dirksen, and Graham, '70). The Montgomery package of subroutines written by Alan Montgomery for Texas A&M University was designed for inexpensive and rapid diagnosis of programs using the less accurate line printer rather than the considerably more expensive plotters available. The programming described herein used the Montgomery package for initial error diagnosis, or "debugging", and only minor changes were then necessary for the more accurate plotters finally used in drawing the figures shown here. All program copies listed in Appendix II were written to operate on the
line printer. All programs and data were entered via the interactive system WYLEUR.
RESULTS AND DISCUSSION

The programs described above yield tabular data and two types of graphic output: outline plots of individual skulls and plots of location of a single anatomical point in a series of skulls. Each of these forms of representing the data has advantages and uses the others do not have.

Table 1 shows representative data in both spherical and rectangular coordinates. Numbers printed in tabular form can be directly compared if the same zero point is used for positioning the skulls in the craniocat. This would be most useful when the anatomical point being studied is changing constantly; otherwise the movement of the point might be difficult to visualize. Tabular data can also be used in calculations such as the distance equation (1). The derived figures can then be compared. Thus, the overall head length can be calculated for different skulls and compared. Tabular presentation of data has another advantage over graphic presentation of data; it generally is more precise. If the exact values are more important than trends, then tabular forms are more useful than graphic forms.

The first graphic form to be discussed is the outline plot of a complete skull. This plot is drawn using approximately fifty points and is a two-dimensional projection of the skull. A plot drawn by this program can be rotated to any viewing angle. This is accomplished by the entry of two rotation angle values into the computer. For example, the rotation angles entered to generate an isometric plot such as Figure 12 (p.29) are -45° and 35.27°. These plots be compared directly to x-ray films, and the same measurements can be made on these plots as on x-ray films. However, the three-dimensional data can be analyzed in other
<table>
<thead>
<tr>
<th>R(MM)</th>
<th>A(DEG)</th>
<th>E(DEG)</th>
<th>X(IN)</th>
<th>Y(IN)</th>
<th>Z(IN)</th>
<th>IDEN</th>
<th>NSPEC</th>
<th>IPEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>00</td>
<td>00</td>
<td>2.01</td>
<td>0.00</td>
<td>0.00</td>
<td>1</td>
<td>70</td>
<td>3</td>
</tr>
<tr>
<td>54</td>
<td>00</td>
<td>08</td>
<td>2.11</td>
<td>0.30</td>
<td>0.00</td>
<td>2</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>51</td>
<td>00</td>
<td>04</td>
<td>2.00</td>
<td>0.14</td>
<td>0.00</td>
<td>3</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>48</td>
<td>00</td>
<td>20</td>
<td>1.78</td>
<td>0.65</td>
<td>0.00</td>
<td>4</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>52</td>
<td>180</td>
<td>22</td>
<td>-1.90</td>
<td>0.77</td>
<td>0.00</td>
<td>9</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>48</td>
<td>05</td>
<td>22</td>
<td>1.75</td>
<td>0.71</td>
<td>0.15</td>
<td>11</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>39</td>
<td>42</td>
<td>12</td>
<td>1.12</td>
<td>0.32</td>
<td>1.00</td>
<td>24</td>
<td>70</td>
<td>2</td>
</tr>
</tbody>
</table>

**TABLE 1.**

Comparison of Spherical and Rectangular Coordinates.
ways and can be used to generate other plots. Outline plots can be overlapped to show differences between skulls of different ages as shown in Figure 4 (p.18) and Figure 7 (p.23).

The second graphic form to be discussed is the plot of the location of a single anatomical point on a cross-sectional or longitudinal series of skulls. Figure 10 (p.27) is a plot of this type and shows the changes which occurred at the anatomical point alveolare. This kind of plot can be used to graphically show patterns of movement of a point. A graphic representation such as this may make visualization of growth patterns easier. Also, these plots can be used for quantification of change.

One shortcoming of these programs is that they are not written to calculate growth rates. Growth rates can only be determined if the ages of the specimens are known. Since detailed age data was unavailable for the specimens used during development of the programs, the programs do not include a way of calculating growth rates.

In order to use these programs for studies dealing with growth rates, two decisions would have to be made, namely the method of measuring time and the establishment of a reference zero.

The decision of how to measure time is not as trivial as may first be imagined. Growth rates can be determined in terms of either chronological age, i.e., time elapsed since birth, or biological age, i.e., stage of dental maturity or closing of certain sutures. It should be noted that because individuals grow at different rates, chronological age does not necessarily equal biological age. Growth can be defined in terms of either kind of age and the computer can handle
either measurement equally well.

The second decision, the establishment of a reference zero, is also more complex than may first appear. The primary problem is constancy of the reference point. Since the skull grows irregularly, all points are moving with respect to each other. One possibility is to establish the reference point somewhere other than on the skull's surface. However, the zero point must be related to the skull so measurements can be repeated on other skulls. Consequently, no reference zero will be totally free from the problem of movement.

A possible solution to this problem could be the definition of a reference plane as well as a reference zero. A previous attempt to standardize cranial measurements resulted in the definition of the Frankfort horizontal plane (defined in Barnicot, '77, p.197). The Frankfort plane was not used in the collection of the data used here; instead the reference plane was alveolare-spheno-occipital suture (Oyen, '74). Both of these planes are perpendicular to the midsagittal plane which separates the skull into left and right halves. Both planes assume that the skull is perfectly symmetrical but it is not, so error could easily be introduced into the measurements. However, if the reference plane is defined unsymmetrically, then the problem of lack of symmetry is lessened. If poirion-bregma-alveolare is used as the reference plane and defined to have an elevation angle of zero, and poirion is used as the reference zero, then all of the measurements taken in Oyen's 1974 work could still be taken. Since the plots can be rotated, the unfamiliarity of the view is unimportant. The most important reason for using this reference plane is the relative stability of the area around poirion (Krogman, '51, p.269).
The reference plane and zero point are crucial. If the only calculations performed on the craniostat data were those of straight-line distance between points on a single skull, then the reference point and plane would be unimportant. Distance calculations involve arithmetic difference. The difference between twenty and ten millimeters is the same as between fifty and forty millimeters. When coordinates are overlapped, then the assumption is made that the zero points are the same. If they are not, then the superimposed plots may show age-related differences in the face in a pattern which does not match what is happening in reality. Because the error can be large if two unequal zero points are equated, the reference plane and zero point should be defined in as reproducible a manner as possible.

Future Research and Applications

Three-dimensional techniques such as the one described herein can be used in many areas of study of craniofacial growth. Most studies of growth are based on linear measurements, not three-dimensional analysis of shape change. Use of linear measurements as the basis of these studies has the underlying assumption that researchers know what the significant linear measurements are. Three-dimensional analysis of shape and form change may show the validity or invalidity of this assumption and may suggest other linear measurements which are better indicators of growth. Two areas where the methodology developed herein has direct application are clinical determination of growth and physical anthropology.

Clinical application of this methodology includes three-dimensional analysis of growth trends. Once a large number of human faces have been measured using the craniostat, standards can be established showing when growth of different
areas is likely to occur. After standards have been established, a person with an orthodontic problem can be measured to determine how severe the problem is and how much worse it is likely to become. Comparison of the problem's severity, the person's developmental age, and the standards can tell the orthodontist what type of corrective measures to take and when to take them. By considering the entire face in three dimensions, the clinician can tell what effects the treatment will have on the overall appearance of the face. Establishment of three-dimensional standards of growth will also allow the clinician to predict the adult form of the child's face. If the potential for a cosmetic problem exists, it may be discovered while the child is young enough for treatment. Orthodontic and cosmetic problems are only two areas of clinical application of this three-dimensional technique.

Possible uses of the craniostat and programs written to analyze craniostat data in physical anthropology include studies of craniofacial growth and behavior in non-human primates and analysis of form and function in fossil hominids. As Sherwood Washburn stated in 1962, "A dynamic analysis of the form of the jaw will illuminate problems of evolution, fossil man, race, growth, constitution, and medical application" (p.92). He also claimed, "to understand behavior, live animals must be studied first, and then, when fossils are found, the attempt can be made to interpret the differences by a knowledge of the living forms" ('62, p.83).

The craniostat can be adapted for use with living animals and the movement of points on the face can be traced during a behavior such as chewing. Once coordinates of the points have been obtained, they can be analyzed by the programs developed here and plots of motion during chewing can
be drawn. Since these are three-dimensional plots, they can be rotated to any viewing angle. The function of various structures could be determined, and this information could be applied to the analysis of fossil forms. This could lead to understanding of the behavior of fossil hominids and determination of selection pressures. An example of this would be the study of baboons as a model for early hominids. Washburn and DeVore ('61) postulated that the baboon, a savannah dweller, has behavioral similarities to early hominids. If the behavior of the baboon can be quantified, then possibly the function of biological structures used in the behavior can be determined. If mastication is studied, perhaps the function of the large canines in males could be determined. If the canines have a major role in mastication, then fossil hominids which lack a large canine probably had a different set of dietary behaviors. However, the size of the canines might not be crucial to mastication and may instead be a defense weapon as proposed by Washburn and DeVore ('61).

Another theory in physical anthropology which might be tested using this three-dimensional technique is the dietary hypothesis of australopithecine variation. Robinson ('52, '54) claimed that the robust and gracile australopithecines represent two genera, differing in dietary behaviors and habitat. He claimed that the gracile australopithecines were omnivores, even hunters, and that the robust australopithecines were specialized herbivores. Other anthropologists have claimed that the australopithecines are a single genus with multiple species (e.g., Greene, '73; Pilbeam and Gould, '74). This is the most common view of australopithecine variation now (Walker and Leakey, '78). Still other anthropologists such as C. Loring Brace ('67) suggested
that the australopithecines were neither two genera nor two
species, but were a single species showing variation due to
sexual dimorphism, racial variation, or local adaptations
(Jolly and Plog, '79, p.195). If the size differences be-
tween the robust and gracile forms are quantified in three
dimensions, they could be compared to the size differences
between males and females in living primates such as the
gorilla. The variation among australopithecines may fall
within the range of variation found in living primates. If
so, the methodology described herein might contribute to
falsification or rejection of the dietary hypothesis of
australopithecine variation.

Since the craniostat was developed specifically to
measure the head, this methodology employing craniostat data
can be applied directly to research on the head. Both cli-
nical and anthropological questions can be addressed by this
method. A three-dimensional approach can be taken rather
than the two-dimensional approaches of linear measurements
and x-ray techniques. Therefore, the techniques and programs
described herein should be of interest to clinicians and
anthropologists alike.
SUMMARY

Three-dimensional description and analysis of biological forms, or biostereometrics, can be a valuable tool in understanding the growth of biological forms. As Oyen, Rice, and Walker ('78) stated, "... biostereometric procedures may be combined with other methods to generate more complete mathematically accurate, and biologically sound characterizations of human form, growth, and development." This project is a combination of a biostereometric technique with computer analysis of data to yield a mathematically accurate, biologically sound, more complete way to describe form, growth and development which can be used in solving anthropological and clinical problems involving quantification of craniofacial growth and development.
LITERATURE CITED


Herron, R. 1972 Biostereometric measurement of body form.


APPENDIX I

GLOSSARY

AMDAHL 470 V/6 - The brand name of Texas A&M University's computer.

COMPILER - A computer program which translates high-level computer commands to machine language commands.

DIGITAL COMPUTER - A computer capable of performing arithmetic and logical functions on numerical data.

FORTRAN - A short form of FORMula TRANslation; a high-level scientific programming language.

HIGH-LEVEL LANGUAGE - A computer language which is not directly readable by the computer; a language in which a single command can represent a complex calculation.

LINE PRINTER - An output machine which prints line by line like a typewriter.

PLOTTER - An output machine capable of drawing curved lines.

PROGRAM - A set of commands written in a computer language.

SPHERICAL COORDINATES - A system of locating points in three dimensions. The points are described as though they were located on the surface of a sphere surrounding an arbitrarily chosen zero point.

SUBROUTINE - A portion of a program which performs part of the function of the program.

WATFIV - A compiler designed to translate FORTRAN programs.

WYLEBUR - An interactive system which allows entry of programs and data from a typewriter-like terminal.
**APPENDIX II**

* * *
* THIS PROGRAM WILL SORT AND PLOT DATA *
* FROM DIFFERENT SKULLS. IT WILL USE A *
* SPECIFIC NUMBER TO IDENTIFY THE SAME *
* (HOMOLOGOUS) POINT ON EACH SKULL. IT *
* WILL PLOT LINES JOINING HOMOLOGOUS *
* POINTS, RATHER THAN PLOTTING POINTS *
* FROM THE SAME SKULL. IT UTILIZES THE *
* SUBROUTINE READIN PREVIOUSLY WRITTEN *
* TO CONVERT SPHERICAL COORDINATES TO *
* RECTANGULAR COORDINATES. *
* * *

COMMON B(3200),A(3200),E(3200),ID(3200),IPEN(3200),
1XENG(3200),YENG(3200),ZENG(3200),NDATA,NSORT,NSPEC(3200)
CALL LINE1(8.5,-5.5,75,-5,1,1.)
CALL READIN
CALL SORT
CALL LINE3 (13.1)
CALL SORTTP
CALL LINE3 (13.1)
CALL SORTPR
CALL LINE3 (13.1)
CALL AXO(3,3,-45.,35.27,50.,5)
CALL PLOT(0.,0.,999)
STOP
END

**SUBROUTINE READIN**

* * *
* THIS SUBROUTINE WILL READ IN DATA IN *
* SPHERICAL COORDINATES AND CONVERT IT *
* TO RECTANGULAR COORDINATES. IT ALSO *
* STORES IT IN AN ARRAY FOR USE IN *
* OTHER SUBROUTINES LATER IN THE SAME *
* PROGRAM. *
* * *
* VARIABLE NAMES AND MEANINGS:
* *
* R=RAD=RADIAL DISTANCE (MM) *
* A=AZI=AZIMUTH ANGLE (DEG) *
* E=ELE=ELEVATION ANGLE (DEG) *
* AZIRAD,ELERAD=AZI,ELE CONVERTED TO *
* RADIANs *
* RADPAC=CONVERSION FACTOR DEG TO RAD *
* X,Y,Z=RECTANGULAR COORDINATES OF R,A,E *
* E *
* XENG,YENG,ZENG=X,Y,Z IN INCHES *
* NDATA=NUMBER OF DATA POINTS *
* ID=IDENTIFICATION NUMBER OF ANATOM- *
* ICAL POINT PLOTTED *
* IPEN= PEN POSITION DURING PLOTTING *
* NSORT=NUMBER OF ID NUMBERS PER *  
* BABOON *  
* NSPEC=SPECIMEN IDENTIFICATION NUMBER *  
*  
**************************************************************************

COMMON R(3200), A(3200), E(3200), ID(3200), IPEN(3200),  
1XENG(3200), YENG(3200), ZENG(3200), NDATA, NSORT, NSPEC(3200)  
RADFAC=3.14159/180.  
L = 0  
READ (5, 105) NDATA  
105 FORMAT (I5)  
WRITE (6, 100)  
100 FORMAT ('1')  
READ (5, 106) NSORT  
106 FORMAT (I5)  
DO 10 I=1, NDATA  
READ (5, 101, END=500) R(I), A(I), E(I), ID(I), IPEN(I), NSPEC(I)  
101 FORMAT (F4.0, F5.0, F5.0, I3, I2, I3)  
L=L+1  
RAD=R(I)  
AZI=A(I)  
ELE=E(I)  
AZIRAD=AZI*RADFAC  
ERAD=ELE*RADFAC  
XENG(I)=RAD*COS(AZIRAD)*COS(ERAD)/25.4  
YENG(I)=RAD*SIN(AZIRAD)/25.4  
ZENG(I)=RAD*SIN(ERAD)*COS(ERAD)/25.4  
10 CONTINUE  
500 NDATA=L  
RETURN  
END  
SUBROUTINE SORT
**************************************************************************

* THIS SUBROUTINE WILL PLOT HOMOLOGOUS *  
* POINTS FROM DIFFERENT SKULLS. IT *  
* WILL ALSO PLOT THE POINTS IN THE *  
* NUMERICAL ORDER OF THEIR ID NUMBERS *  
* THIS WILL ENABLE THE PROGRAM TO BE *  
* TESTED SIMPLY AND QUICKLY. *  
* THE VARIABLE NAMES ARE THE SAME AS *  
* IN SUBROUTINE READIN. *  
**************************************************************************

COMMON R(3200), A(3200), E(3200), ID(3200), IPEN(3200),  
1XENG(3200), YENG(3200), ZENG(3200), NDATA, NSORT, NSPEC(3200)  
IDE=1  
DO 20 I=1, NDATA  
IF(ID(I).NE.IDE) GO TO 20  
XPLT=XENG(I)+3.  
YPLT=YENG(I)+3.  
IP=3  
19 CALLPLOT(XPLT, YPLT, IP)  
20 CONTINUE  
CALL PLOT(0., 0., 3)
CALL PLOT(0.,0.5,2)
CALL SYMBOL(0.,0.55,0.15,105,-1)
CALL PLOT(0.,0.,3)
CALL PLOT(0.5,0.,2)
CALL SYMBOL(.55,0.,0.15,103,-1)
CALL PLOT(0.,0.,3)
RETURN
END

SUBROUTINE SORTPR

******************************************************************************

*              *
* THIS SUBROUTINE WILL USE DATA FROM  *
* SUBROUTINE READIN AND PLOT THE TOP  *
* VIEW OF THE MOVEMENT OF ANATOMICAL  *
* POINTS  *
* IT ALSO PRINTS THE AXES IN THE LOWER  *
* CORNER AND LABELS THEM  *
* THE VARIABLE NAMES ARE THE SAME AS  *
* IN SUBROUTINE READIN  *
*  
******************************************************************************

COMMON R(3200),A(3200),E(3200),ID(3200),IPEN(3200),
1XENG(3200),YENG(3200),ZENG(3200),NDATA,NSORT,NSPEC(3200)
IDE=1
DO 20 I=1,NDATA
   IF(ID(I).NE.IDE)30 TC 20
   XPL=ENG(I)+3.
   YPL=ENG(I)+3.
   IP=3
   CALLPLOT(XPL,YPL,IP)
20 CONTINUE
CALL PLOT(0.,0.,3)
CALL PLOT(0.5,0.,2)
CALL SYMBOL(0.,0.55,0.15,105,-1)
CALL PLOT(0.,0.,3)
CALL PLOT(0.5,0.,2)
CALL SYMBOL(.55,0.,0.15,103,-1)
CALL PLOT(0.,0.,3)
RETURN
END

SUBROUTINE SORTFR

******************************************************************************

*              *
* THIS SUBROUTINE WILL USE DATA FROM  *
* SUBROUTINE READIN AND PLOT THE FRONT  *
* VIEW OF THE MOVEMENT OF ANATOMICAL  *
* POINTS  *
* IT ALSO PRINTS THE AXES IN THE LOWER  *
*  
******************************************************************************
COMMON R(3200),A(3200),E(3200),ID(3200),IPEN(3200),
1XENG(3200),YENG(3200),ZENG(3200),NDATA,NSORT,NSPEC(3200)
IDE=1
DO 20 I=1,NDATA
IF(ID(I),NE.IDE)GOTO 20
XPLT=ZENG(I)+3,
YPLT=YENG(I)+3,
IP=3
19 CALLPLOT(XPLT,YPLT,IP)
20 CONTINUE
CALL PLOT(0.,0.,3)
CALL PLOT(0.,0.5,2)
CALL SYMBOL(0.,0.55,0.,15,104,-1)
CALL PLOT(0.,0.,3)
CALL PLOT(0.5,0.,2)
CALL SYMBOL(0.55,0.,0.15,105,-1)
CALL PLOT(0.,0.,3)
RETURN
END

SUBROUTINE AXO(XTR,YTR,THETA PHI,PRJDIS,SP)

***************
*THIS SUBROUTINE WILL USE DATA FROM *
*SUBROUTINE READIN AND PLOT THE AXO *
*VIEW OF THE MOVEMENT OF ANATOMICAL *
*POINTS *
*THE VARIABLE NAMES ARE THE SAME AS *
*IN SUBROUTINE READIN *
*
***************

COMMON R(3200),A(3200),E(3200),ID(3200),IPEN(3200),
1XENG(3200),YENG(3200),ZENG(3200),NDATA,NSORT,NSPEC(3200)
STHETA=SIN(THETA/57.3)
CTHETA=cos(THETA/57.3)
Sphi=SIN(PHI/57.3)
Cphi=COS(PHI/57.3)
IDE=1
DO 20 I=1,NDATA
IF(ID(I),NE.IDE)GOTO 20
XPLT=(XENG(I)*CTHETA*ZENG(I)*STHETA)*SF
YPLT=(XENG(I)*CTHETA*Sphi+YENG(I)*Cphi-ZENG(I)*CTHETA*
1Sphi)*SF
ZPLT=(-XENG(I)*STHETA*Cphi+YENG(I)*Sphi+ZENG(I)*CTHETA*
1Cphi)*SF
XPERS=XPLT/(1.-ZPLT/PRJDIS)+XTR
YPERS = YPLOT/(1-ZPLOI/PRJDIS) + YTR
CALL PLOT(XPERS,YPERS,3)
20 CONTINUE
RETURN
END
VITA

Name: Kathleen Lowry Eaves
Born: November 14, 1954  Lakewood, Ohio
Parents: Charles G. and Evelyn N. Lowry
Permanent address: 8200 Westview, Houston, TX 77055
Professional experience:
1972-1975  Welch Undergraduate Fellow, Chemistry Department, Texas A&M University under Dr. F.A. Cotton. Modeled hormone active sites by x-ray crystallography and kinetic methods. American Institute of Chemists Outstanding Student Award. 
1975-1977  Technician I, Agricultural Analytical Services, Texas A&M University. Analyzed medicated feeds and pesticide formulations for state regulatory lab. Sole responsibility for medicated feeds lab. Published one paper and presented it at national meeting, American Chemical Society.
1978-1979  Graduate Assistant, Non-teaching, Department of Sociology and Anthropology, Texas A&M University. Wrote and graded tests for introductory physical anthropology classes. One paper in press, presentation scheduled for national meeting, American Association for the Advancement of Science.
1979-  Technician I, Agricultural Analytical Services, Texas A&M University. Analyzed pesticide formulations under contract to federal regulatory lab. Developed in-house methods. Professional memberships: American Association for the Advancement of Science, American Association of Physical Anthropologists, American Chemical Society, Phi Lambda Upsilon.