TECHNIQUES FOR SIMULATING CRANIOFACIAL CHANGE

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Introduction

The simulation of several distinct types of craniofacial changes are discussed in the context of two-dimensional coordinate models of craniofacial morphology. Specifically, data accumulated from serial x-ray films are used, in conjunction with the model, to simulate:

(a) Normal and aberrant craniofacial growth and development

(b) Orthodontic correction of malfunctions of the teeth and jaws

(c) Oral surgical procedures of jaw rotation, resection and bone displacement

(d) Craniofacial injuries incurred during automobile accidents and their treatment and

(e) The evolution of the human skull.

We first describe the model and then consider its application to these problems in turn.

The Model

We describe the model in the context of its implementation in practice, i.e., the steps involved in proceeding from the original cephalogram to the numerical image of this cephalogram as recorded on punched cards or magnetic tape. The first step in the procedure is to trace the original x-ray film on a sheet of transparent matte acetate. The matte acetate is firmly fastened over the surface of the x-ray film and the outlines of the skull bones and dentition are traced. The structures actually traced are illustrated in Figure 1.

Tracing is a relatively skilled operation and we have found that it takes several months to train a technician to carry out this procedure with reasonable reliability. We have checked the variation in the tracings from one technician to another using the same x-ray films and find that there is relative consistency between the tracings of the same technician, but a higher variance between the tracings of two or more technicians. We have introduced quality controls at this stage by carefully checking, and if necessary correcting, the tracings as they are completed. Where possible we try to keep the variation to within ± 0.5 mm for each point. We have found that many of the points can be seen very clearly on the x-ray and that these have relatively low variation; other points are more difficult to locate and these are recorded with a somewhat lower level of confidence. When higher accuracy is required, we repeat the tracings and average the measurements.

The next step in the recording procedure is to carefully mark the 177 coordinate points which comprise our mathematical model on the tracing, as illustrated in Figure 2. The indicated points include all of the traditional anthropometric landmarks as well as intermediate points which are added so that we have a sufficient number of points to reliably describe the curve of the skull bones. For example, on the sagittal outline of the parietal bones the only well-defined anatomical points are at the extremities, these being Lambda (point #20) towards the posterior and Bregma (point #47) at the anterior end. To describe the curve of the skull vault between these two points we divide the parietal curve into eight segments and a point marks the junction of each segment. These intermediate points are included among those depicted in Figure 2, which shows the outlines of the skull bones and the 177 points which make up our model. In order that each cephalogram be recorded in a consistent manner, it is necessary to define an origin (this is traditionally positioned at Sella point #95) and also to define a horizontal so that all of the skull images will be in the same relative horizontal plane. For this, we generally take the line from point #16 to point #135, i.e. the line from the base of the occipital bone to the center of the palate, but the orientation of the coordinate system is quite arbitrary and may be shifted depending on the purposes of a given investigation.

The next step is to place the marked tracing on an electronic scanning device (digitizer), such as the Benson-Lehner OSCAR, and set the machine so that the coordinate axes are centered at Sella point (say) and in the proper orientation. The technician then starts at point #1 and continues in an unbroken sequence from #1 to #177, so that all the points are recorded consecutively on punched cards. To operate the machine, two potentiometers are turned so that cross-hairs are brought into position over the marked points and then a recording button is pressed on the digitizing machine. The voltage levels from the two potentiometers (which record the x and y coordinate values as voltage levels) are then transmitted to an analog-to-digital converter and the digital information is fed to a keypunch machine which automatically punches the required coordinate values on cards.

Thus, the measuring and recording procedure consists of three stages: the tracing of the cephalogram, the marking of the 177 coordinate points, and the recording of the numerical values of the coordinates of these points on punched cards using an electronic scanning device. The procedure transforms the information contained in the cephalogram into xy-coordinate values which may be stored as cards or converted to magnetic tape and thus be available for processing on a digital computer. An extremely rich data base can now be generated from these coordinate values: lines, planes, projections, areas, distances and angles are immediately available by the elementary use of coordinate geometry. Statistical analyses can then be carried out on various sets of measurements of interest. Of course, it should be emphasized that the reliability of such analyses is affected by the reliability of the underlying measurements. In recognition of this, considerable care was taken with the measuring procedures employed in order to minimize the magnitudes of the measurement errors and, when possible, to obtain reliable estimates of these errors. In practice, however, the "acid test" of whether or not the procedure is workable is to test if the recorded coordinates of the mathematical model accurately reflect the information contained in the tracing and the x-ray film. To check for gross errors we display the recorded coordinates on a CRT. In this way, errors are easily identified and are corrected before inclusion into the data banks which are to be subjected to statistical analysis.

More rigorous testing may be accomplished by simply having the computer plot the values for comparison and an example of such a pot is given in Figure 3. Here the points are connected by simple straight lines, but other methods of attempting to "reproduce the tracing" from the data banks (e.g., spline-fitting) are certainly possible. These plots are scaled to be comparable to the tracing and x-ray and these are superimposed to check on the goodness-of-fit. We might remark that by using the 177 points, and straight lines to connect these points, we are able to essentially reproduce the tracing and it is in this sense that we claim our model retains much of the informational content and descriptive power of the cephalogram. In any event, this model has proved to be of considerable value in cross-sectional studies of craniofacial morphology and, when longitudinal data are available, can be used to study the growth patterns of selected variables.

In the next section we describe our approach to the study of the growth pattern of the entire collection of coordinate points. We feel that such a study is more valuable than a study concentrating on only a selected number of linear and/or angular variables inasmuch as the growth of each of the components of the craniofacial complex can be followed, allowing a more detailed consideration of shape changes than is possible using traditional methods. However, should one wish to follow the growth of any derived measurement, e.g., mandibular length, this variable is easily extracted from the model and its growth may be studied by conventional procedures.

Growth Vectorgrams

A vectorgram is, simply, the observed growth trajectory associated with any one of the 177 coordinate points comprising the model. Let the position of point j ($j=1,\cdots,177$) for individual i ($i=1,\cdots,N$) at time t_k ($k=1,\cdots,K_i$; $t_1 \cdots t_{K_i}$) be denoted by:

$$P_i(t_k) = \left[X_{ij}(t_k), y_{ij}(t_k)\right]. \qquad (1)$$

Then the vectorgram of the i^{th} individual for point j is denoted by:

$$V_{ij} = \left[P_{ij}(t_1),\cdots,P_{ij}(t_{K_i})\right] \qquad (2)$$

and the vectorgram set for individual i is defined as the matrix (with matrices as elements):

$$\begin{bmatrix} P_{i1}(t_1) & \cdots & P_{i1}(t_{K_i}) \\ \cdot & & \cdot \\ \cdot & & \cdot \\ P_{i,177}(t_1) & \cdots & P_{i,177}(t_{K_i}) \end{bmatrix} = \begin{bmatrix} V_{i1} \\ \cdot \\ \cdot \\ V_{i,177} \end{bmatrix} \qquad (3)$$

The model (3), however, is a rather complicated one for evaluating change. In Horst's (1) terminology, we have sets of data matrices containing measures on each of a number of attributes (the xy-coordinate values) for each of a number of entities (individuals) for each of a number of conditions (genetic and/or environmental groupings) taken on each of a number of different occasions. Horst surveyed the problems associated with the analysis of models of this general structure and concluded that, "The general problem is extremely complex and no adequate solutions are currently available". Even if we concentrate on a single individual and a fixed point we have what amounts to a bivariate time series where, e.g., the true growth trajectory may be assumed to be a polynomial or other function of time. But the analysis of the data by ordinary time series methods is complicated by the fact that the time points will not in general be equally spaced and, when more than one individual is considered, we may have very different observation time sequences $t_1,\cdots,t_{K_i}$ to contend with and, often, individuals will have different numbers of total observations. Nor is it clear in the two-dimensional case how one can mirror the pubertal spurt and other characteristic features of growth curves in terms of a tractable bivariate function of time. In an attempt to circumvent these difficulties we have, as a first approximation at least, considered fitting the observed x-coordinate increments to time, say $x=g(t)$, and then assuming that the corresponding y-values are given by a polynomial in $x=g(t)$. Fitting the polynomial by least squares we have found that a quadratic function generally fits the data quite well, the coefficients in the regression equation being estimated by combining vectorgrams for similar individuals. The resultant regression equations:

$$\begin{aligned} x &= g(t) \\ y &= ax^2 + bx + c \end{aligned} \qquad (4)$$

constitute what we call the composite vectorgram when the vectorgrams of several individuals are used to estimate the quadratic regression of y on x; when only a single individual is involved we refer to (4) as the smoothed vectorgram. This formulation of the problem is tractable inasmuch as growth curves $g(t)$, as well as their derivatives $g'(t)$, for marginal growth and rate of change of growth in the x-direction are readily available and can be used to interpolate within (and extrapolate beyond) various observation time sequences $t_1,\cdots,t_{K_i}$ and to reflect the pubertal spurt as well as other features of the typical (marginal) growth curve. For example, suppose we observe a given child at 6.3, 7.1, 10.4 and 13.2 years of age. From the marginal growth function $g(t)$ we can obtain estimated values of x at $t = 6,7,\ldots,18$ (say) so that we can compare and/or combine this child's growth pattern with those of other children and predict how this given child will grow, the corresponding y-values being obtained by the estimated quadratic in $x=g(t)$. The fitting of y as a quadratic in x can then be thought of as simply a device for smoothing vectorgrams, or for producing smoothed composite vectorgrams. These composite vectorgrams can then be assembled for each of the 177 points for some group of individuals and growth projections for similar individual and growth projections for similar individuals obtained.

Mean Value Simulation; Growth Projections

Suppose we are given a group of N homogeneous individuals and serial cephalograms for each. We can then average the vectorgrams of these individuals for each of the 177 points (or for some suitable subset of these points) to obtain a set of smoothed composite vectorgrams. Then given a new individual of the same type we could, in the absence of any additional a priori information, obtain a growth projection by simply assuming that this new individual will grow according to the mean growth trajectory of his peer group. As growth proceeds, the actual and predicted values may be compared and updated projections obtained. Thus it is possible to simulate growth activity using the averages of the observed growth trajectories of a number of like individuals (this is called an "expected value simulation model"), giving an indication of what the child could be expected to look like if he were to follow the average growth pattern of his peers. An illustration is given in Figure 4 where the growth trajectories associated with point #138 (Pogonion) are plotted for seven different individuals from eight to twelve years of age. These data may then be averaged and the corresponding annual growth increments plotted to give the clinician some insight into the structural changes that accompany "average growth." In this way standards for normal development like those shown in Figure 5 for females from 6 to 12 years of age can be derived.

Figure 4 can, of course, be extended to show more than a single growth increment. Figure 6 shows the average growth pattern for the entire constellation of points (again, these are connected by simple straight lines) for several years. Plots of this kind are especially valuable to the clinician inasmuch as they clearly reveal the predicted future size of craniofacial structures, the future relationships between these structures, the timing of certain structural changes, and the velocity and direction of future growth. For a more detailed discussion, see Walker and Kowalski (2).

We are currently in the process of preparing a large volume of data on orthodontic case histories. We have already prepared a large volume of normative data collected over a period of some twenty years by Dr. W. M. Krogman at the Philadelphia Center for Research in Child Growth. Our aim is to amalgamate this information to form a dynamic system of diagnosis which considers the patient's progressive growth changes, evaluates his facial growth potential against norms for his age and maturation, and plots and tabulates the expected growth increments for the ensuing years under various treatment regimens and, in effect provides the framework of evidence within which an effective treatment plan may be designed. This has obvious clinical importance, but may also be recognized as a useful teaching device allowing the student to see the estimated long-term effects of a particular treatment in a matter of seconds. We are also experimenting with direct manipulation of the parameters in (4) and have been able to find, e.g., a set of functions $g(t)$, defined over a sufficiently long time interval, which agrees quite closely with the evolutionary changes which must have occurred if Man did evolve from the lower primates. This is discussed in more detail in a later section. More details on the simulation of orthodontic treatment strategems were given by Walker and Kowalski (3).

Simulation of Oral Surgical Procedures

The simulation of a number of oral surgical procedures, including jaw rotation, surgical resectioning and bone displacement, was previously described by Walker and Kowalski (4). In this paper we concentrate on but two examples, vis., (1) "open bites" (a condition in which the patient cannot bite on his front teeth) and (2) the severe Angle class III malocclusion (a condition in which there is a marked protrusion of the mandible, or lower jaw, resulting in the lower teeth biting anterior to the upper teeth). Both the immediate and long-term effects of the treatments are considered and, in the latter case, we simulate subsequent growth and development not only on the basis of "normal" growth and development data, but also when the growth pattern which caused the anomaly in the first place can be expected to continue unabated even in the face of surgical intervention as can occur, e.g., in patients with acromegaly (a condition caused by a tumor on the pituitary gland resulting in a much longer than normal growth period for certain bodily structures, including the mandible).

Available treatment strategems for the correction of open bites correspond to mandibular rotations and several of these, corresponding to different oral surgical procedures, may be simulated using our system. The simplest approach to treatment is to reduce or eliminate the premature molar contact (which prevents the patient from biting on his anterior teeth) by grinding or extracting the molar teeth. This allows more complete rotation of the mandible and may bring the incisors into occlusion. In cases where these more conservative measures cannot be expected to produce incisal contact, surgical resectioning of the jaw, where the lower portion of the mandible is rotated until the incisors occlude, may be necessary. In any event, these procedures may be simulated, and their relative efficiencies compared, before any treatment is undertaken. Simulation may show that simply grinding or extracting the molars will allow sufficient mandibular rotation to close the bite but, even should more extreme measures be required, this preliminary evaluation is valuable inasmuch as it quantifies the position and amount of change, or resectioning, required.

In the surgical treatment of severe class III malocclusions, surgical resectioning is often used, i.e., a "cut and slide" repositioning of the mandibular structures in an attempt to achieve normal dental occlusion and facial harmony. This permits posterior translation of the lower half of the mandible, bringing it more in line with the maxillary structures. The surgical approach may vary from a horizontal resection of the ramus slightly above the level of the lower molars to the complete removal of of a block of bone in the mid-portion of the body of the mandible, but each such approach may be quantified in the context of a translation of some portion of the mandible. Thus, these operations may be simulated by the technique described so that the position of the ostectomy and the amount, shape and region of bone removal may be varied and the subsequent changes evaluated by the surgeon.

Simulation of Craniofacial Injuries

The model can also be used to simulate craniofacial injuries incurred in automobile accidents and their treatment. This was previously described by Walker and Kowalski (5) and will be illustrated at the conference in the form of a movie taken directly from a cathode ray tube. In particular, the movies will show injuries invloving the forehead, mid-face and upper and lower jaws, for both drivers and passengers, with and without seat belts, etc. Methods of treatment, extending the notions described in the preceeding section, will also be considered.

Simulation of Skull Evolution

Since our coordinate model can accomodate the skull morphology of all primates, it can also be used to simulate evolutionary changes in the human skull. Examples of how several primates have been described in the context of our model are shown in Figure 8 and a description of the uses and limitations of the corresponding simulation model is given by Walker and Kowalski (6). Here we discuss only the background for this approach - illustrations will again be provided at the conference in the form of a movie.

Ever since the time of Darwin the fossil record of man and other primates has both enlightened and confused the story of Man and his evolution. A major problem in piecing the story together is the fragmentary nature of the evidence.

Our data are mainly the fossil remains of early primates from the Miocene and Pliocene ages (some 25 million years to 3 million years ago). Then appeared what may be regarded as the early ancestors of man, i.e. the Australopithecines, in the late Pliocene and early Pleistocene ages (approximately 1 to 2 million years ago). The Pleistocene glacial age commenced approximately 1 million years ago, and has continued with cold and warmer periods down to modern times. Most of the human fossils date from this period and some of the older anthropological names such as Pithecanthropus erectus, Sinanthropus pekinensis, Homo modjokertensis, Heidelberg man and Java man, may be familiar to most readers. Once these were classified as separate genera, but the tendency nowadays is to group them under the generic title of Homo erectus. More modern forms such as Neanderthal and Cromagnon man, are thought to date from about 50,000 - 30,000 years ago, and these together with the living races of man are grouped under the heading of Homo sapiens, such as Homo sapiens neanderthalensis and Homo sapiens sapiens.

In the case of other evolving mammals such as the horse, there is a very complete fossil record, showing gradual transitions or transformations along a relatively direct course. The transformation of the Lower Eocene or "dawn horse" eohippus into the modern horse is perhaps the most complete record of this kind.

It is unlikely that man's evolution has been as direct or "linear" as that of the horse, and several theories have been postulated other than the linear hypothesis which suggests man evolved in a comparatively stratight line from primitive to modern forms. A more widely accepted theory is one which could be called a tree or branching theory, in which many of the fossil forms diverged from the main stem at some point in time to form their own sub-species of the hominid range. This branching or divergence may be a result of "genetic drift", possibly caused by population isolation and inbreeding after migrations to new lands, or environmental changes brought about by the ice ages. A third possibility, and one which is finding increasing acceptance in modern times, may be called the reticular or network theory of human evolution. This presupposes that the various tribes or groups were of the same species and interfertile, hence after a period of isolation and "divergence" they could later merge together again, and gene flow would form a new "pooled" population. This pattern of reticular development accelerates under any circumstances in which communication or contact between populations is increased. Historically, this tends to follow the conquest of one population by another, and under conditions where the invaders settle permanently, interracial admixture becomes very common. Modern examples are the Anglo-Indians of India, the Cape colored of South America and the Chicanos of North America.

If one takes the skull as a biological entity in which many genetic forces can be expressed, then the study of the evolution of the human skull presents an intriguing mathematical and biological challenge. It is to this end that we have produced mathematical models of the human skull and brain and simulated transformation of the skull shapes from Pleistocene times through to modern man. The particular simulation model we are presenting is a simplistic one and based upon a linear model of development. In other words, in this example we ignore extreme variants or probable "branches" and thus follow the median forms, but of course it is possible to simulate these branching changes if suitable decision theory can be applied. The reticualr theory of evolution would form an extremely complex simulation model in which the branch changes could diverge and converge as a complicated net. In the current model we are simulating changes from early hominids to modern man, assuming that evolutionary changes are in small increments (based upon the survival of many small mutations) and that these may be represented as small steps or transformations in the simulation model. As the model is based upon curvilinear equations it becomes possible to project these to a hypothetical future time, and simulate the possible evolutionary changes during, for example, the next half a million years. It should be noted that this simulation projection assumes that the evolutionary process will continue and will not be entirely modified by man's intervention. It is highly probable, however, that cultural and technological developments will foster such techniques as genetic selection, which may completely change the course of human evolution.

Summary

Techniques for the simulation of several types of craniofacial changes were discussed and illustrated in the form of movies presented at the conference. These films have proved to be particularly valuable as teaching devices for those involved in the study of anthropology, growth and development, orthodontics and oral surgery.

References

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(5) Walker, G.F. and Kowalski, C.J. Simulation of craniofacial injuries incurred in automobile accidents. Proc. 1975 Summer Computer Simulation Conference. Simulation Councils, Inc., La Jolla, 851-855.

(6) Walker, G.F. and Kowalski, C.J. Simulation of human skull evolution. Proc. 1973 Summer Computer Simulation Conference. Simulation Councils, Inc., La Jolla, 811-813.

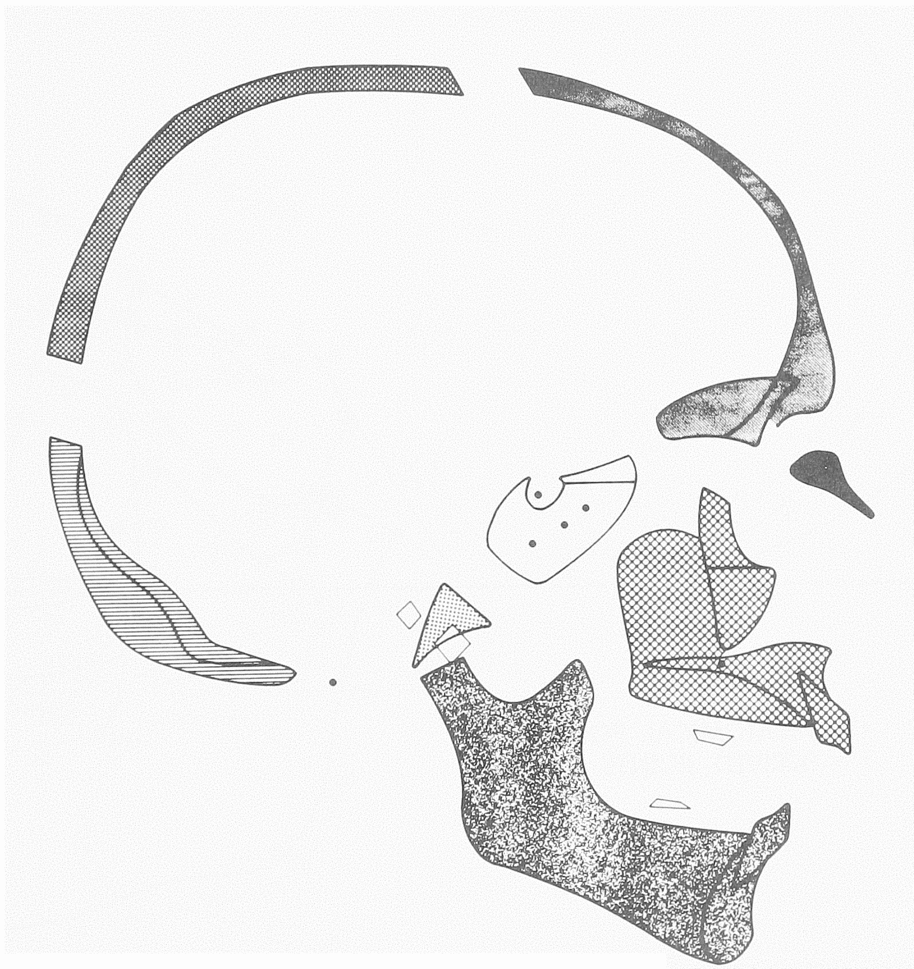

Figure 1. The morphological structures comprising the geometrical model.

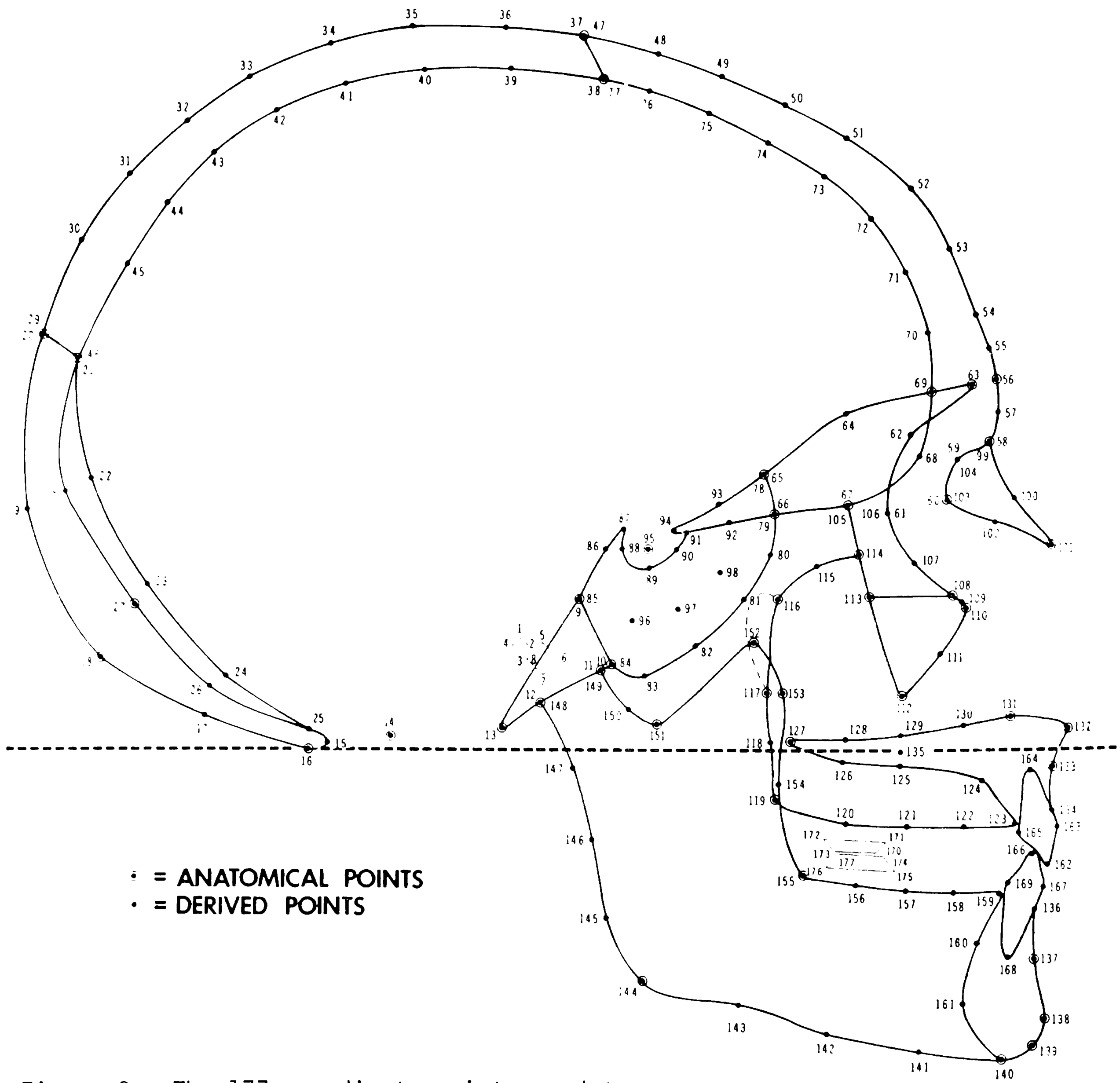

Figure 2. The 177 coordinate points used to describe craniofacial morphology.

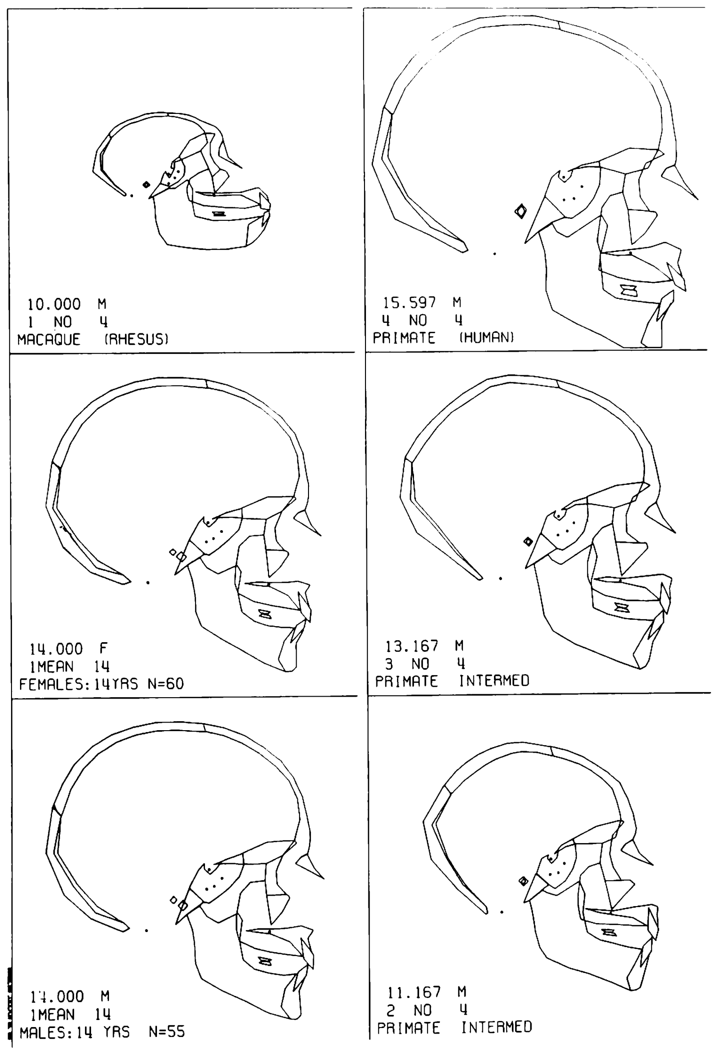

Figure 3. Examples of computer-drawn plots of craniofacial morphology.

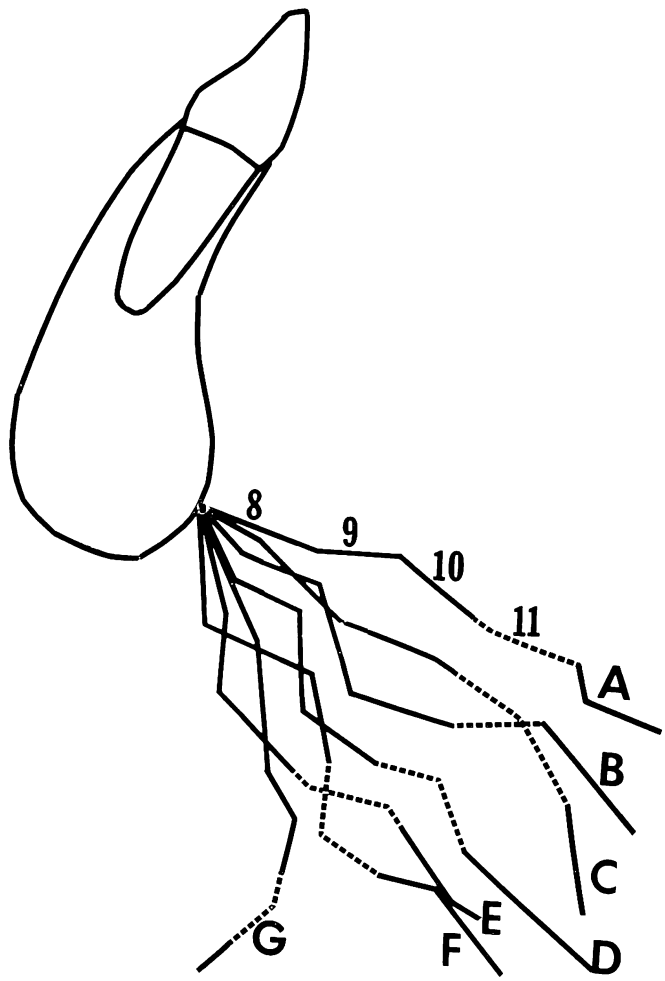

Figure 4. Growth vectorgrams associated with Pogonion.

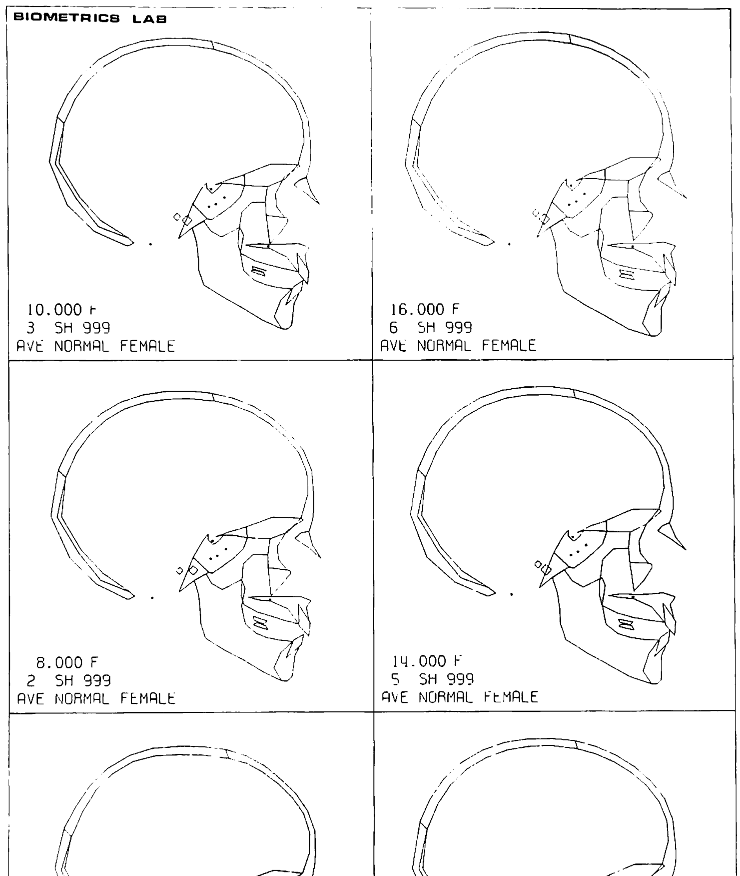

Figure 5. Average craniofacial morphology of females from 6 - 16 years of age.

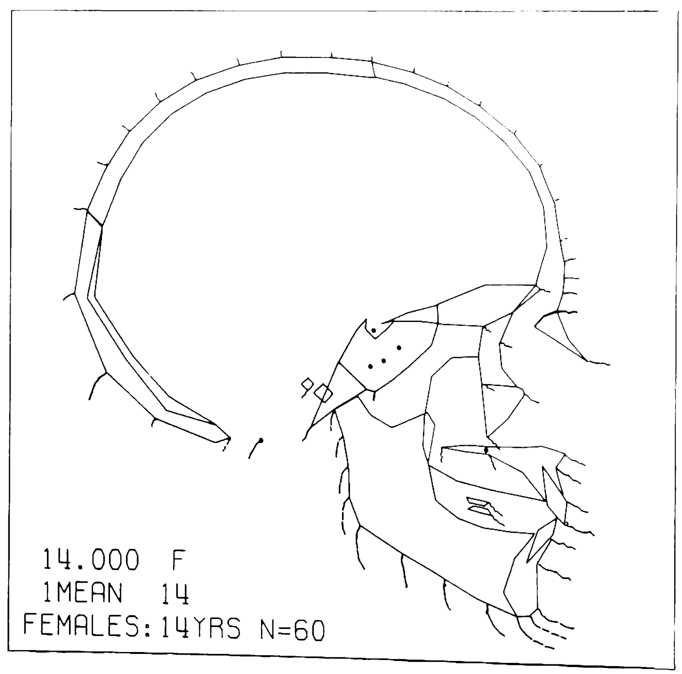

Figure 6. Growth vectorgrams associated with several anatomical points.

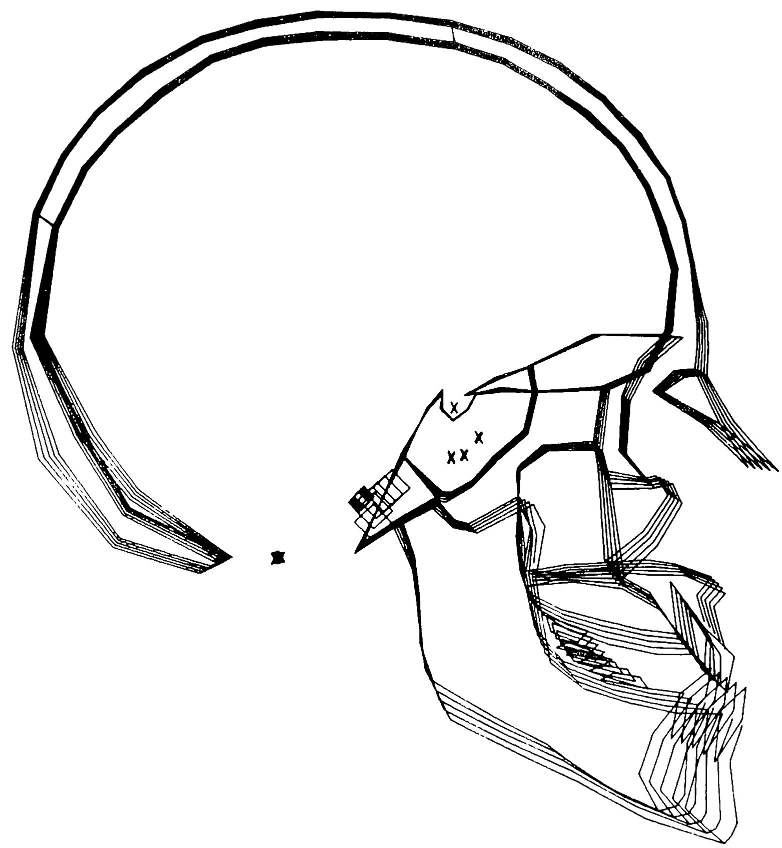

Figure 7. Simulated development of a class III malocclusion.

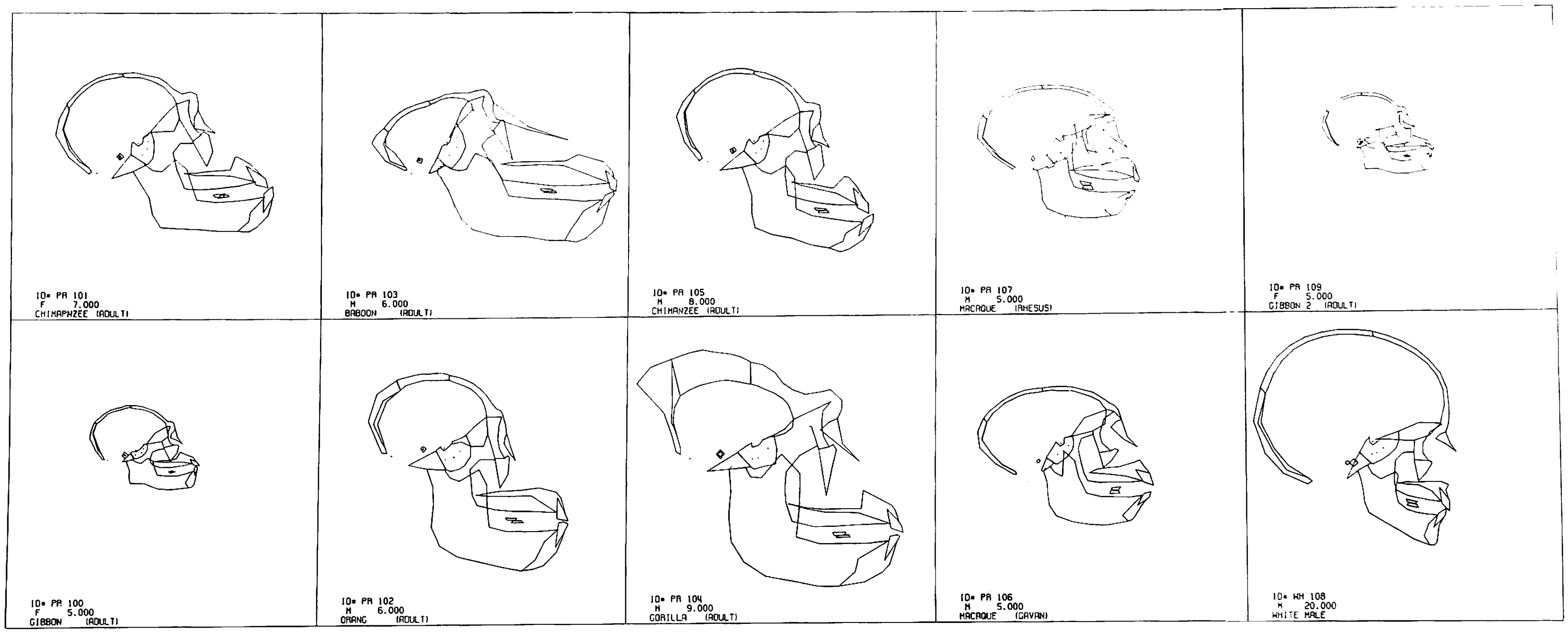

Figure 8. The craniofacial morphology of several primates.