# The stability of anatomical and centroid reference points in cephalometric analysis

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Standard cephalometric analysis generally depends upon superimposition of successive x-rays or tracings. Because certain geometric and conceptual constraints are involved, the use of such methods has been called into question recently by some authors including Moyers and Bookstein[1] and Moss et al.[2-4] The ultimate biological correctness of any description of growth will depend on the stability of the reference points chosen. If growth is described by the changes of all other structures relative to a given set of reference points then arbitrary selection of another set of reference points will lead to still another description of growth. The question arises, is it possible to determine mathematically whether any one of these several alternate descriptions is more nearly correct than the others. Standard cephalometric analysis has depended on the concept of privileged point locations which are assumed to be fixed.

Johnson[5-7] approached the fixed point problem using the centers of gravity. Every particle is attracted towards the center of the earth by the force of gravity and the center of gravity or centroid of a body is the point where the resultant force of attraction acts. The centroid is that point around which a body hangs freely in equilibrium when it is suspended in a gravitational field. The center of gravity of a two-dimensional image is a center of area, not mass.

The centroid of an image is influenced by an infinite number of points around the perimeter of the shape and the distribution of area within the shape. Because all the single elements in the shape contribute to the centroid position, the centroid has the properties of a mathematical 'mean.' The centroid represents the 'mean' point of a shape about which it varies and, like other means, is subject to the least amount of variation in relation to (non-mean) anatomical points.[8]

Evidence that centroid points are less variable than anatomical points has been derived by quantifying and comparing the variation of angles and distances between every combination of pairs of defined lines and points (both anatomi-

**Abstract**

Cephalometric records of 60 fetuses were combined on a coordinate reference grid to measure the statistical spread of the outlines. When centroid instead of anatomical points were used for superimposition of records, the spread of the outlines was reduced dramatically, being statistically significant ($p<0.0001$). The centroid is a mean point being less variable and preferable to anatomical points commonly used for comparing successive cephalometric records.

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**Key Words**

Cephalometrics • Variation • Centroid • Reference points

cal and centroid). The mean variance can then be calculated for each of the angles and points measured. Centroid angles and points come out with the least variance in such studies.[6,9]

The objective of centroid analysis is not to provide a mathematical formula to describe growth, which is a very complex and variable process, but rather to produce a statistical approach to growth representation which is less dependent upon individual variation. In a purely morphological context growth may be considered as a change in size and shape with time. Craniofacial morphology depends on the interaction of many single genes and multiple environmental factors. These multifactorial effects result in biological variation approximating to a normal distribution. Thus, craniofacial morphology along with many other biological characteristics approximates to the laws of statistics and probability.

Variation can be measured by recording the statistical spread of a series of outlines that are superimposed on one another. One method of doing this is by the use of analytical histomorphograms.[10] The location of a series of outlines on the coordinate grid using the fixed relations between three anatomical points enables the measurement of variation of the outlines in the form of analytic histomorphograms. By recording the mean, one standard deviation and two standard deviation outlines, biological variation can be measured. By recording a sufficiently large number of cases such variation approximates to a 'normal' or Gaussian distribution. This was performed for fetal skull outlines using both anatomical and centroid points for superimposition.[11-13]

The purpose of the present study was to compare the variation in outlines of tracings using either centroid or anatomical points for superimposition in order to see if there was any statistically significant difference.

The results of the study have important applications in clinical practice for determining the stability of cephalometric datum points, the choice of which is important when comparing records of different patients or the same patient at different times.[7]

## Materials and methods

Sixty fetuses ranging from 49 millimeters to 212 millimeters, crown-rump length (2.5 to 5.5 lunar months gestation) were studied. They were derived from both spontaneous and therapeutic abortions and were preserved in formalin.

The standard analytic morphograph[14-16] was modified to take fetal material by the use of smaller ear pieces. In the lateral view the thick arms of the main cephalostat obscured more of the fetal head than was acceptable. To overcome this problem an auxiliary cephalostat was designed which fit into the body of the main cephalostat.[17]

The coordinate reference system was built into the photographic and radiographic recording system so that only the fetus needed to be adjusted before directly comparable records could be produced. The same ear-ear-left orbitale convention was used as for the postnatal method.[14-16] In this convention the midpoint between the tips of the two ear pieces within the external acoustic meatus was placed at the origin of the rectangular coordinate reference grid to produce two-element symmetry. A third element was defined by marking the left orbitale. This was constrained to lie on a reference plane fixed within the recording apparatus so as to produce three-element planar freedom.

Records were produced in the form of photographs and radiographs taken in the frontal, lateral and basal positions. The records were traced with pen and ink on cellulose acetate sheets. The tracings were processed on the University of Manchester Computer Graphics Unit. The image outlines were digitized in segments so that by adding them in various combinations different components of the image could be analyzed. A program was written to enlarge the image outlines of the skull component to a standard area of 30,000 square millimeters, to eliminate the effect of size at various ages.

The sized outlines (for each of the X, Y and Z views) were combined for all 60 fetuses to produce histomorphograms. Using computer programs, outlines were derived for the mean, for one standard deviation, and two standard deviations. It was not appropriate for the current study to produce such histomorphograms of all 60 fetuses without adjusting the size because of the high growth rate during the fetal period and the consequent large differences in size of the image outlines in relation to the size of the sample studied. The operation was performed initially for the adjusted image outlines using the midpoint between the earpieces within the external auditory meati and the left orbitale for orientation, Figures 1a to 6a. The centroid was then calculated for the whole skull outline together with the cranium and face components. All three centroids form a straight line, the craniofacial centroid plane. The centroids for the 60 fetuses were plotted on the reference grid and their mean position determined. The operation was repeated on the same data but adjusted to the mean skull centroid and orientated on the

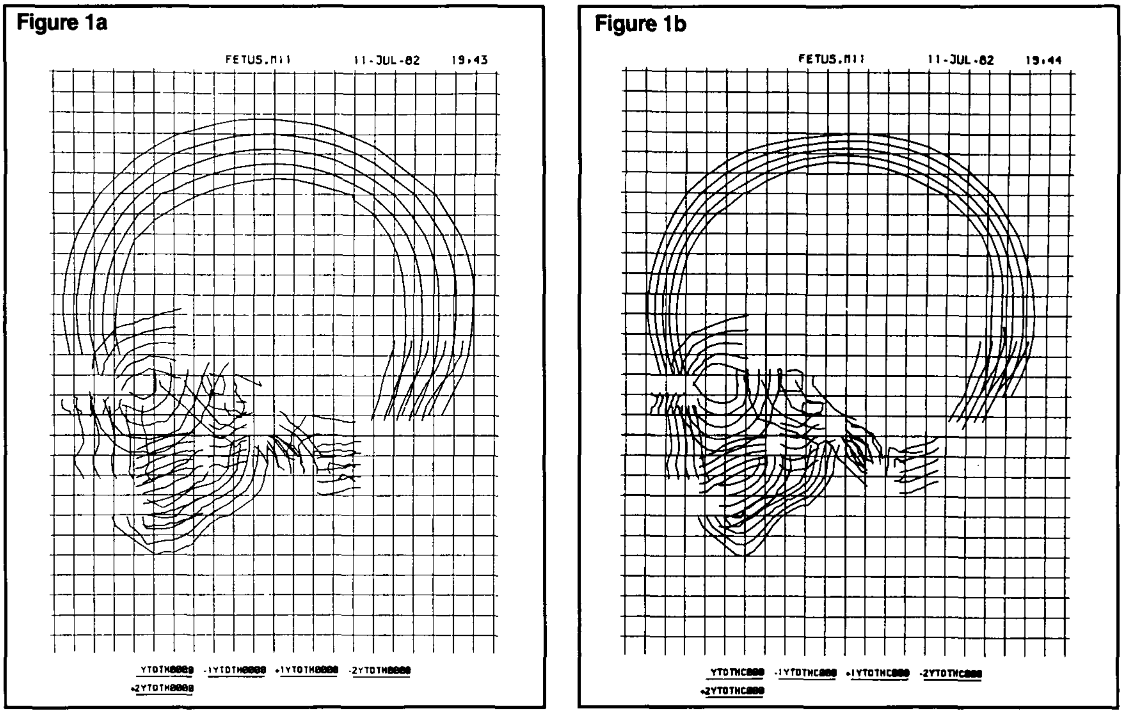



**Figure 1**
**Histomorphograms of lateral view radiographs.**
**a. Anatomical points.**
**b. Centroid points.**

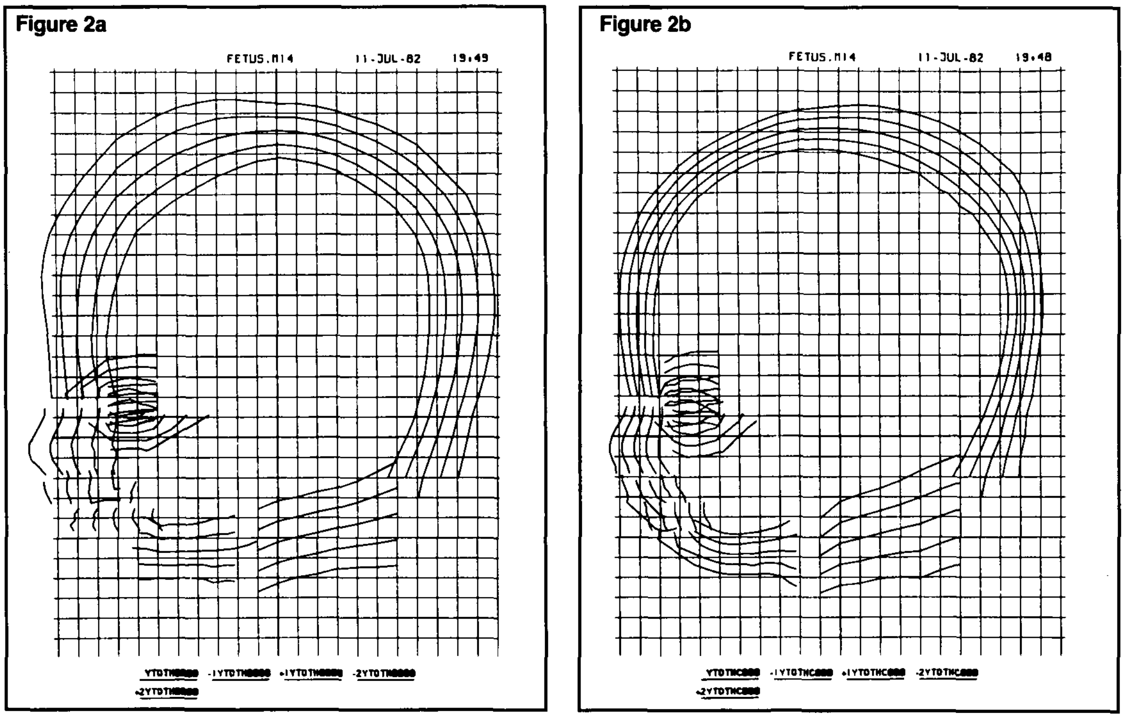



**Figure 2**
**Histomorphograms of lateral view photographs.**
**a. Anatomical points.**
**b. Centroid points.**

mean craniofacial centroid line, Figures 1b to 6b. Measurements of the spread of the histomorphograms between the two standard deviation lines (±2S.D.) were taken at regular intervals along the outlines, Table 1. The spread of the outlines related to the reference grid by anatomical points was compared statistically to that using centroid points. As the data were matched a paired *t*-test was performed, Table 2.

Systematic errors which bias measurement by a constant factor were minimized by accurate calibration of the analytic morphograph. Such errors would show up on the records because the ear-ear-left obitale orientation points would not relate to the rectangular coordinate reference grid correctly.

Random errors were assessed by repeating measurements on 10 cases and finding the variation during digitizing, tracing and radiographic recording. For each stage the difference between the first and second operation was found and the mean difference for the group was calcu-

**Figure 3**
**Histomorphograms of frontal view radiographs.**
**a. Anatomical points.**
**b. Centroid points.**

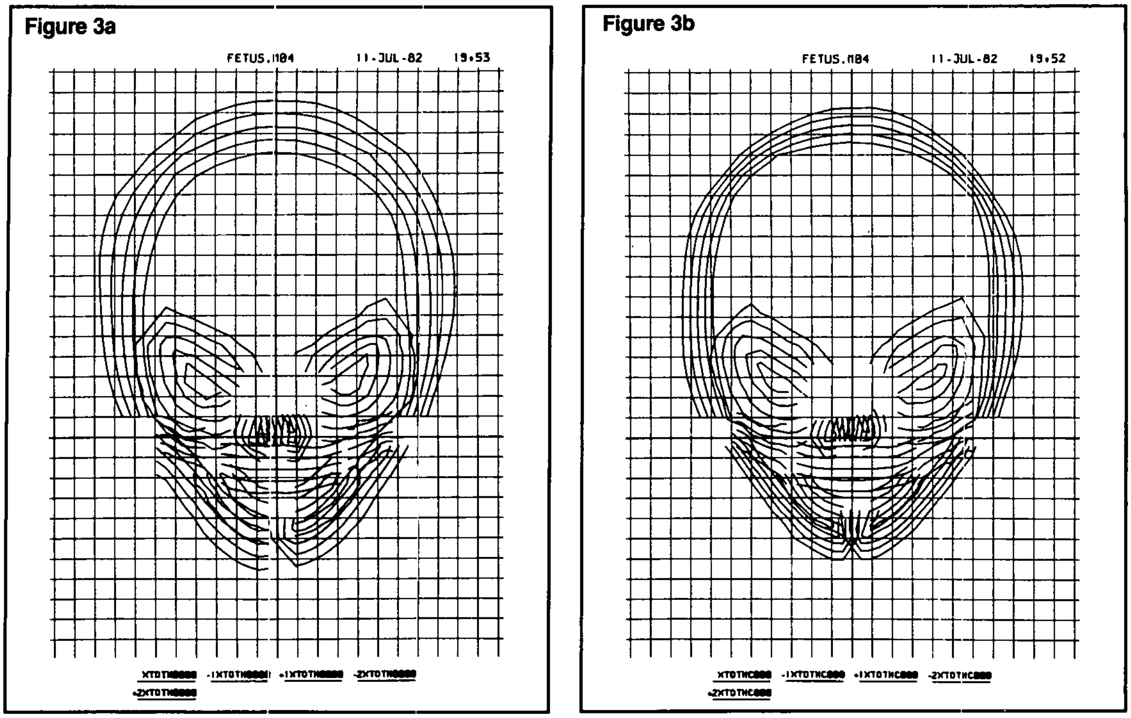
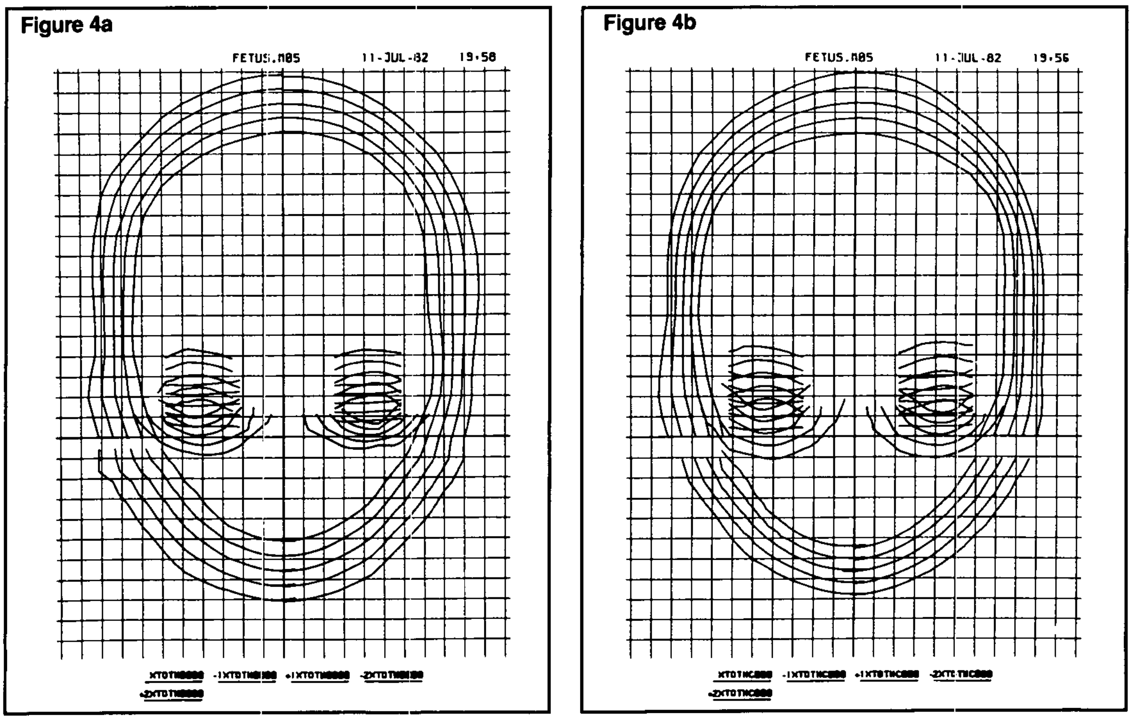



**Figure 4**
**Histomorphograms of frontal view photographs.**
**a. Anatomical points.**
**b. Centroid points.**




lated. The error was derived by dividing the mean difference by the mean value and expressing it as a percentage. The greatest error, 1.5 percent, was in tracing the radiographs. Taking a second record only involved an error of 1.4 percent, less than the tracing error. Hence, the analytic morphograph is an extremely accurate recording apparatus.

The error in redigitizing was only 0.17 percent, considerably less than tracing and recording the radiograph, reflecting the high degree of accuracy achieved by the electronic computer.

## Results

For hard and soft tissue outlines in frontal, lateral and basal views there was a large and obvious reduction in spread when centroid points were used instead of anatomical points.

By comparing Figures 1a through 6a with Figures 1b through 6b it was clear that the spread of the one standard deviation and two standard deviation outlines was considerably

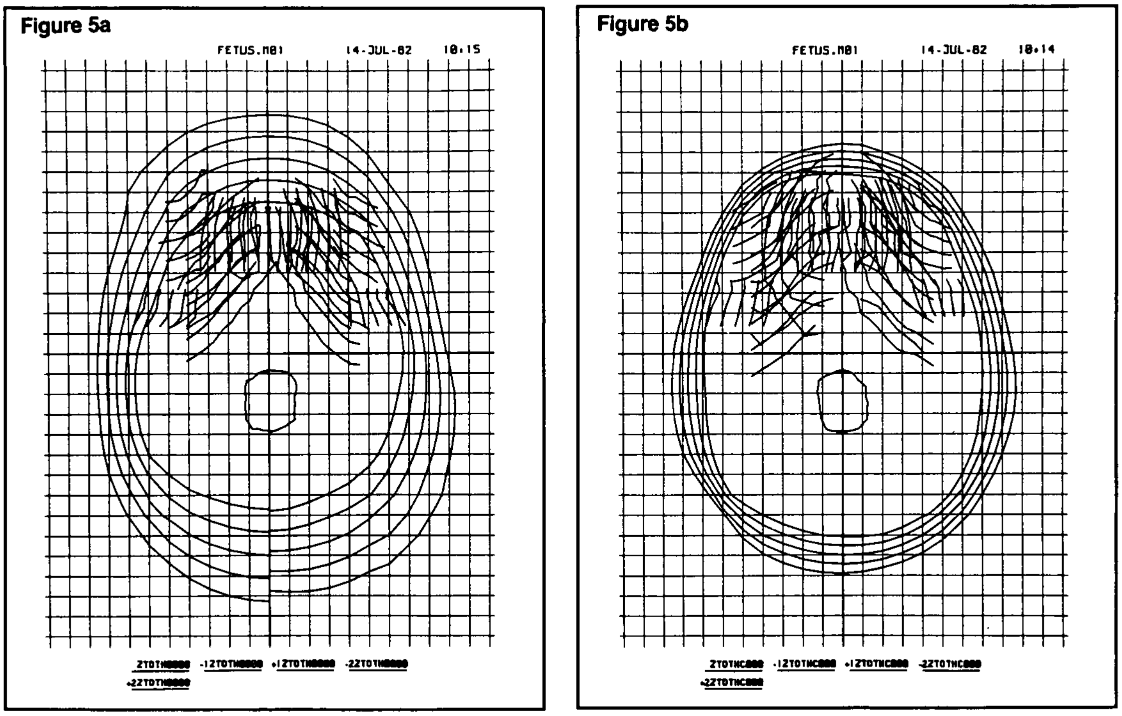



**Figure 5**
**Histomorphograms of basal view radiographs.**
**a. Anatomical points.**
**b. Centroid points.**

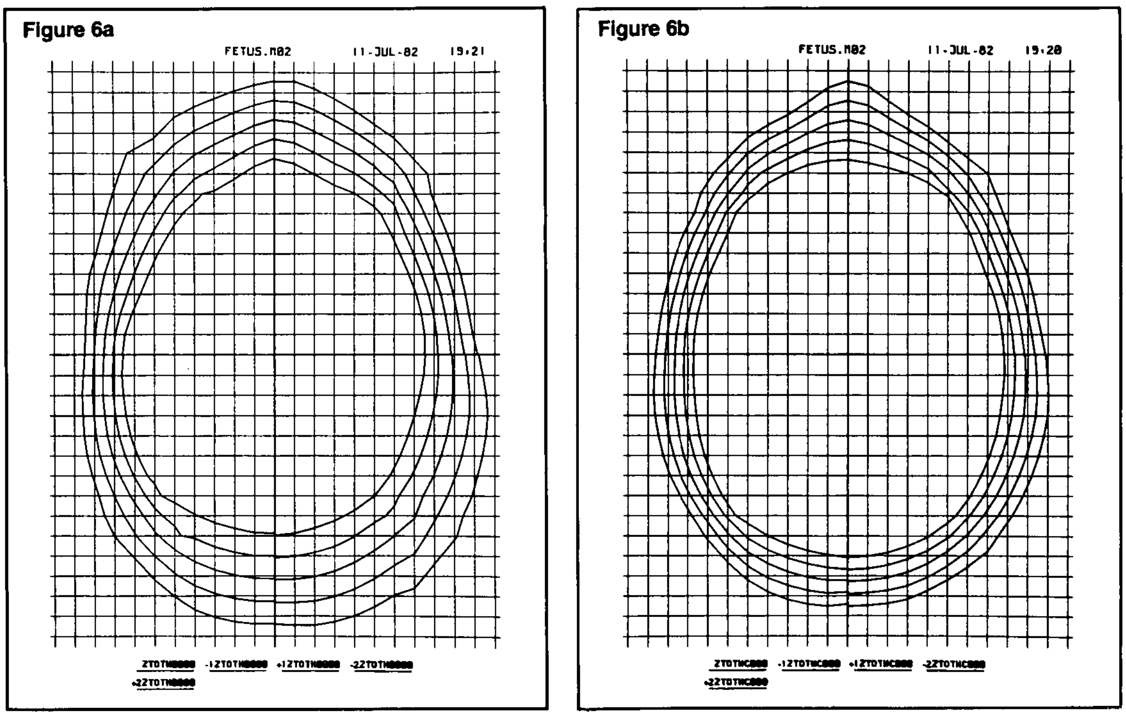



**Figure 6**
**Histomorphograms of basal view photographs.**
**a. Anatomical points.**
**b. Centroid points.**

reduced in all cases when centroid points were used for superimposition and that the mean outlines were virtually unaffected. Also, there was a slight increase in the spread for the soft tissue outline of the eye especially on the left side, because the left orbitale was used in the orientation of the forms for imaging.

As the mean and standard deviation lines had been derived from a sample of fetuses of varying ages, both cross-sectional and longitudinal variation was represented. It is important to note that the variation was increased in regions where marked growth changes occurred.

The spread of the two standard deviation outlines was measured at intervals around each of the tracings Figures 1a and 1b—6a and 6b and recorded in Table 1. A *t*-test was performed to see if there was a statistically significant difference in the spread produced by superimposing on anatomical and centroid points Table 2. For each of the views recorded there was a highly significant reduction in spread when centroid

**Table 1**

**Distances (mm) between +2SD and -2SD taken at intervals along the outlines of Figs. 1-6a & b.**

| | 1a | 1b | 2a | 2b | 3a | 3b | 4a | 4b | 5a | 5b | 6a | 6b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 22.0 | 12.0 | 25.0 | 24.0 | 10.5 | 8.0 | 19.0 | 22.0 | 17.0 | 11.0 | 20.5 | 16.0 |
| | 24.0 | 15.0 | 25.0 | 21.0 | 10.5 | 9.0 | 18.0 | 20.0 | 16.0 | 11.0 | 18.5 | 15.0 |
| | 25.0 | 16.0 | 24.0 | 19.0 | 12.0 | 9.0 | 16.0 | 17.0 | 15.5 | 11.0 | 19.0 | 14.5 |
| | 26.0 | 16.0 | 22.0 | 16.0 | 13.5 | 10.5 | 15.0 | 14.5 | 16.0 | 11.0 | 18.0 | 15.0 |
| | 26.0 | 16.0 | 22.0 | 16.0 | 15.5 | 12.0 | 15.5 | 14.0 | 17.0 | 11.0 | 19.0 | 15.0 |
| | 27.0 | 14.5 | 22.5 | 14.0 | 17.5 | 12.5 | 17.0 | 15.0 | 18.5 | 11.0 | 19.0 | 15.0 |
| | 26.0 | 13.0 | 24.0 | 13.5 | 19.0 | 12.5 | 19.0 | 14.5 | 20.0 | 10.0 | 20.0 | 14.5 |
| | 24.0 | 12.5 | 24.5 | 13.5 | 19.0 | 12.5 | 20.0 | 14.5 | 21.5 | 9.0 | 20.0 | 15.0 |
| | 23.0 | 12.0 | 25.0 | 14.0 | 19.0 | 12.0 | 20.0 | 14.5 | 24.5 | 9.0 | 23.0 | 16.5 |
| | 21.0 | 13.0 | 26.0 | 14.0 | 18.5 | 10.0 | 20.0 | 14.0 | 30.0 | 9.0 | 25.0 | 17.0 |
| | 20.0 | 13.0 | 25.0 | 14.0 | 17.5 | 10.0 | 19.0 | 13.0 | 32.0 | 9.0 | 25.5 | 18.0 |
| | 21.0 | 14.0 | 25.0 | 14.5 | 18.0 | 7.0 | 19.0 | 12.0 | 33.0 | 10.0 | 29.0 | 21.0 |
| | 22.0 | 13.0 | 24.0 | 17.0 | 19.0 | 8.0 | 19.0 | 12.5 | 33.0 | 11.5 | 33.0 | 25.0 |
| | 22.0 | 12.0 | 25.0 | 20.5 | 18.5 | 9.0 | 18.0 | 15.0 | 33.0 | 11.5 | 32.5 | 28.0 |
| | 22.0 | 12.0 | 24.0 | 22.5 | 19.0 | 10.0 | 18.0 | 15.0 | 33.0 | 11.5 | 31.0 | 30.0 |
| | 23.0 | 11.0 | 24.0 | 22.5 | 19.5 | 12.0 | 18.0 | 18.0 | 33.0 | 10.0 | 30.0 | 28.0 |
| | 23.5 | 10.5 | 23.0 | 22.0 | 20.0 | 13.5 | 19.0 | 20.0 | 32.0 | 9.0 | 31.0 | 23.0 |
| | 21.0 | 12.0 | 23.0 | 21.5 | 19.5 | 13.5 | 20.0 | 22.0 | 30.0 | 8.5 | 31.0 | 20.0 |
| | 21.5 | 11.0 | 22.0 | 21.0 | 19.0 | 13.0 | 22.0 | 23.0 | 25.0 | 8.0 | 32.0 | 19.0 |
| | 21.5 | 11.5 | 22.0 | 20.0 | 20.0 | 13.0 | 22.0 | 23.0 | 21.0 | 7.5 | 30.0 | 18.0 |
| | 21.0 | 12.0 | 22.0 | 19.0 | 19.5 | 12.0 | 22.5 | 23.0 | 20.5 | 8.0 | 30.0 | 16.5 |
| | 24.0 | 10.5 | 21.0 | 17.0 | 19.0 | 10.5 | 22.5 | 22.0 | 20.0 | 7.5 | 26.0 | 15.0 |
| | 24.0 | 11.0 | 23.0 | 16.0 | 18.0 | 8.5 | 22.5 | 22.0 | 19.0 | 8.0 | 24.0 | 15.0 |
| | 24.0 | 13.0 | 25.0 | 15.0 | 17.5 | 9.0 | 22.0 | 20.0 | 16.5 | 9.0 | 23.0 | 14.0 |
| | 24.0 | 14.0 | 28.0 | 15.0 | 17.5 | 8.5 | 22.0 | 19.0 | 15.0 | 10.0 | 21.5 | 14.5 |
| | 24.0 | 14.0 | 30.0 | 14.0 | 19.0 | 9.0 | 21.0 | 17.5 | 14.5 | 10.5 | 20.5 | 14.0 |
| | 22.5 | 13.5 | 31.0 | 13.5 | 20.0 | 11.5 | 19.0 | 17.0 | 14.5 | 12.0 | 17.5 | 14.0 |
| | 22.0 | 13.0 | 32.0 | 13.5 | 20.0 | 11.5 | 18.0 | 16.0 | 14.5 | 12.5 | 15.0 | 14.0 |
| | 20.5 | 11.0 | 32.0 | 14.0 | 19.0 | 11.5 | 19.0 | 15.0 | 15.0 | 13.0 | 15.0 | 14.5 |
| | 19.0 | 10.5 | 30.0 | 13.5 | 18.0 | 11.0 | 18.0 | 14.0 | 16.5 | 12.5 | 15.5 | 15.0 |
| | 19.0 | 10.0 | 29.0 | 14.0 | 16.0 | 11.5 | 16.5 | 14.0 | 19.0 | 12.5 | 17.0 | 16.0 |
| | 24.5 | 11.0 | 29.5 | 14.0 | 16.0 | 11.5 | 16.5 | 14.0 | 23.0 | 11.0 | 17.0 | 16.0 |
| | 24.0 | 11.5 | 30.0 | 14.0 | 15.5 | 12.0 | 16.0 | 12.5 | 26.0 | 9.0 | 18.0 | 16.0 |
| | 28.5 | 13.0 | 28.5 | 14.0 | 15.0 | 12.0 | 15.5 | 11.5 | 29.0 | 7.0 | 19.0 | 16.0 |
| | 25.5 | 15.0 | 27.0 | 13.0 | 14.0 | 12.0 | 15.0 | 11.5 | 33.0 | 9.0 | 20.0 | 15.0 |
| | 16.5 | 12.0 | 24.5 | 13.0 | 14.0 | 12.0 | 14.0 | 13.0 | 35.0 | 13.0 | 22.5 | 15.0 |
| | 19.5 | 13.5 | 23.0 | 12.5 | 14.0 | 11.0 | 14.5 | 15.0 | 35.5 | 14.0 | 25.0 | 14.0 |
| | 20.0 | 16.0 | 22.0 | 11.5 | 14.0 | 8.0 | 18.0 | 18.0 | 33.0 | 14.5 | 30.0 | 15.0 |
| | 25.0 | 21.0 | 23.5 | 11.0 | 14.5 | 9.0 | 20.0 | 19.0 | 32.0 | 14.0 | 34.0 | 18.0 |
| | 21.0 | 16.0 | 24.5 | 10.5 | 15.0 | 9.0 | 21.5 | 20.0 | 33.0 | 14.0 | 35.0 | 20.0 |
| | 21.5 | 19.0 | 28.0 | 15.0 | 16.0 | 9.0 | 22.0 | 20.5 | 34.0 | 13.5 | 36.0 | 20.0 |
| | 21.0 | 17.0 | 31.0 | 19.0 | 17.0 | 10.0 | 24.0 | 15.5 | 34.0 | 13.0 | 35.0 | 20.0 |
| | 21.0 | 15.0 | 31.5 | 18.0 | 20.0 | 11.0 | 23.5 | 18.0 | 34.0 | 12.0 | 35.0 | 20.0 |
| | 24.5 | 17.0 | 26.0 | 20.0 | 21.0 | 10.0 | 23.0 | 17.5 | 33.0 | 12.0 | 35.0 | 19.5 |
| | 14.0 | 12.0 | 30.0 | 22.0 | 10.0 | 11.0 | 24.0 | 17.0 | 30.0 | 11.5 | 36.0 | 19.0 |
| | 14.0 | 11.0 | 20.0 | 15.0 | 12.5 | 10.0 | 24.5 | 17.5 | 28.0 | 10.0 | 37.0 | 19.0 |
| | 14.0 | 11.0 | 20.5 | 15.5 | 12.0 | 10.0 | 24.0 | 17.0 | 26.0 | 105 | 37.0 | 20.0 |
| | 13.5 | 10.5 | 21.5 | 15.5 | 12.0 | 10.0 | 23.0 | 17.0 | 25.0 | 11.5 | 37.0 | 19.0 |
| | 17.0 | 15.0 | 24.5 | 16.5 | 11.0 | 9.0 | 23.0 | 17.5 | 23.5 | 12.0 | 39.0 | 19.0 |
| | 19.0 | 13.0 | 32.0 | 20.0 | 11.0 | 9.0 | 23.0 | 17.5 | 22.0 | 13.0 | 37.0 | 18.0 |
| | 19.0 | 12.0 | 32.0 | 28.5 | 11.0 | 9.0 | 23.0 | 17.5 | 19.0 | 12.5 | 35.0 | 18.0 |
| | 19.0 | 12.0 | 32.0 | 32.5 | 11.0 | 9.0 | 24.0 | 17.5 | 17.0 | 12.5 | 31.0 | 18.0 |
| | 16.5 | 10.0 | 17.5 | 17.0 | 17.5 | 11.0 | 24.0 | 17.5 | 19.0 | 17.0 | 30.0 | 18.0 |
| | 18.5 | 15.0 | 21.0 | 19.0 | 18.0 | 16.0 | 23.5 | 17.5 | 18.0 | 19.0 | 29.5 | 18.0 |
| | 17.0 | 11.0 | 12.0 | 16.0 | 18.0 | 17.0 | 21.0 | 17.5 | 21.0 | 19.0 | 28.5 | 18.0 |
| | 15.0 | 8.0 | 13.0 | 17.0 | 17.0 | 16.5 | 21.0 | 18.0 | 19.0 | 20.0 | 25.5 | 18.0 |
| | 14.0 | 8.5 | 22.0 | 17.0 | 15.0 | 15.0 | 21.0 | 18.0 | 19.0 | 20.0 | 23.0 | 17.5 |
| | 14.0 | 10.0 | 17.5 | 16.0 | 18.0 | 17.0 | 21.0 | 18.0 | 18.0 | 18.0 | 21.0 | 16.5 |
| | 15.0 | 10.0 | 18.5 | 16.0 | 19.0 | 17.0 | 20.0 | 20.0 | 21.0 | 19.0 | 20.0 | 15.0 |
| | 22.0 | 17.0 | 19.0 | 15.0 | 20.0 | 20.0 | 19.0 | 19.0 | 21.5 | 18.0 | 20.0 | 15.5 |
| MEAN | 20.9 | 12.9 | 24.7 | 16.8 | 16.5 | 11.2 | 19.9 | 17.1 | 24.1 | 11.9 | 26.3 | 17.6 |
| SD | 3.7 | 2.5 | 4.5 | 4.1 | 3.1 | 2.6 | 2.8 | 3.0 | 7.0 | 3.3 | 7.1 | 3.5 |

points were employed confirming the graphic changes seen in Figures 1a and 1b—6a and 6b.

## Discussion

When any method of superimposition and registration of successive tracings is used, the description of growth will vary depending on the reference points and line segments chosen for superimposition. Determining whether any one of these several alternate descriptions is more nearly correct than the others will depend on the stability of the reference points chosen.

When comparing two samples in standard numerical statistics the mean is the statistic of choice because it shows less variation than individual values and more accurately reflects the population from which the samples are drawn. The distribution of the means of samples of a population shows less variation than the distribution of the individual values; the standard error is always less than the standard deviation.

Similarly, when comparing two shapes the centroid is the point of choice for superimposition because it shows less variation relative to other anatomical points than any of the anatomical points do to each other. The centroid is a measure of central tendency and possesses many of the qualities of a mathematical mean. It is in this sense, the least variable and the most stable point. Thus, it is least affected by fluctuations in sampling. Should an individual subject present an abnormality in the architecture of a skull, the abnormality will tend to be absorbed and the center will deviate only slightly. This is clearly shown by the marked reduction in the spread of the one standard deviation and two standard deviation outlines when centroid points were used for superimposition rather than anatomical points. This was demonstrated for both photograms and radiograms in the frontal, lateral and basal views and was statistically significant.

Centroid analysis in common with all other coordinate methods involving superimposition of tracings is dependent on the concept of privileged point locations which are assumed to be 'fixed' (least variable). However, in the case of the centroid points there is strong statistical justification to support the concept that even if they are not fixed they are least variable. The present study supports the mathematical evidence derived by Johnson[6,9] that centroid points and angles show the least variance when measured statistically.

There are situations where information is produced independently of the constraints of privileged point locations. For example, the tensors of finite element analysis cannot be readily visualized when being expressed as a set of numbers.[4] While the tensors of finite element analysis may also be graphically depicted[18] the reference system changes along with the form.

**Table 2**
***T*-test for the difference in spread of histomorphograms (± 2SD) using anatomical (Figs. 1a-6a) and centroid (Figs. 1b-6b) points for superimposition.**

| Figure | *T*-Value | Probability |
|---|---|---|
| 1a-1b | -18.63 | 0.0001 |
| 2a-2b | -10.69 | 0.0001 |
| 3a-3b | -12.54 | 0.0001 |
| 4a-4b | - 8.09 | 0.0001 |
| 5a-5b | -11.69 | 0.0001 |
| 6a-6b | -12.13 | 0.0001 |

In all reference frame dependent methods, changes in form are plotted relative to a reference system which is independent of changes in the form. Where successive tracings or radiographs are superimposed there has to be a reference system common to all records for valid comparisons to be made. As a consequence of their reduced variance and greater stability, centroid points have an important role to play in the location of any chosen reference system.

## Conclusions

Photographs and radiographs of the craniofacial region were taken on 60 fetuses in the frontal, lateral and basal views. The tracings of the records were combined in a coordinate reference grid to measure the variation in spread of their outlines. This was performed using both anatomical and centroid points for superimposition.

- The spread of the outlines observed graphically was considerably reduced in all cases when centroid points were used for superimposition.
- A *t*-test showed a highly significant ($p < 0.0001$) reduction in the spread when centroid points were used.
- The centroid is a measure of central tendency and possesses many of the qualities of a mathematical mean and as a consequence is the least variable and most stable point.

- Centroid points have an important place in the location of successive tracings on a common reference system in order to make valid comparisons between records.

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## References

1. Moyers, R.E. and Bookstein, F.L.: The inappropriateness of conventional cephalometrics. Am. J. Orthod., 75:599-617, 1979.
2. Moss, M.L., Skalak, R., Dasgupta, G. and Vilmann, H.: Space time and space time in craniofacial growth. Am.J. Orthod., 77:591-612, 1980.
3. Moss, M.L., Skalak, R., Shinozuka, M., Patel, H., Moss-Salentijn, L., Vilmann, H. and Mehta, P.: Statistical testing of an allometric centered model of craniofacial growth. Am. J. Orthod., 83:5-18, 1983.
4. Moss, M.L., Skalak, R., Himanshu, P., Kasturia, S., Moss-Salentijn, L., Masanobu, S. and Vilmann, H.: Finite element method modeling of craniofacial growth. Am. J. Orthod., 87:453-472, 1985.
5. Johnson, J.S.: The use of centres of gravity in cephalometric analysis: a preliminary report. Dent. Practit. Dent. Rec., 10:107-113, 1960.
6. Johnson, J.S.: A statistical survey, illustrating the uses of mathematical centres, in the analysis of human lateral skull cephalostat radiographs. PhD Thesis, University of London, 1972.
7. Johnson, J.S.: A new approach to cephalometric analysis of the dental base relationship. Angle Orthod., 48:23-32, 1978.
8. Johnson, J.S.: Recent developments in diagnosis and treatment planning of antero-posterior jaw discrepancies from the lateral skull cephalostat radiograph. Br. J. Oral Surg., 17:256-264, 1979a.
9. Johnson, J.S.: A method of assessing the hierarchy of variation of craniofacial lines in cephalometric analysis. IRCS Med. Sci., 7:60, 1979b.
10. Rabey, G.P.: Morphanalysis of craniofacial dysharmony. Brit. J. Oral Surg., 15:110-120, 1977b.
11. Trenouth, M.J.: The measurement of fetal craniofacial growth by computer graphic centroid morphanalysis. PhD Thesis, University of Manchester, 1983.
12. Trenouth, M.J.: Shape changes during human fetal craniofacial growth. J. Anat., 139:639-651, 1984.
13. Trenouth, M.J.: Changes in the jaw relationship during human foetal craniofacial growth. Br. J. Orthod., 12:33-39, 1985.
14. Rabey, G.P.: Morphanalysis, Manchester: Centre for Morphanalysis, 1968.
15. Rabey, G.P.: Craniofacial morphanalysis. Proc. Roy. Soc. Med., 64:103-111, 1971.
16. Rabey, G.P.: Current principles of morphanalysis and their implications in oral surgical practice. Brit. J. Oral Surg., 15:97-109, 1977a.
17. Trenouth, M.J. and Rabey, G.P.: Fetal craniofacial morphanalysis. J. Morphanalysis, 1:49-53, 1979.
18. Lozanoff, S. and Diewert, V.M.: Measuring histological form change with finite element methods: an application using diazo-oxo-norleucine (DON) treated rats. Am. J. Anat., 177:187-201, 1986.