Skeletal jaw relationships: a quantitative assessment using elliptical Fourier functions

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Contemporary orthodontic practice requires reliable and valid classifications of skeletal jaw relationships. Although clinicians and researchers have attempted to translate cephalometric measurements into skeletal classification or diagnostic categories,[1-4] there is no evidence to suggest that any one of the conventional skeletal measures is well-suited for this purpose. In addition, the agreement between anteroposterior skeletal classifications based on cutpoints derived from normative data is poor.[4]

Conventional cephalometric analysis (CCA) is designed to measure regularly shaped geometric objects rather than irregular morphological forms. When a complex biological form such as the craniofacial complex is reduced to lines and angles much of the information concerning the true shape of the object is lost.[5] Although multivariate analyses[1,6-9] have been applied to cephalometric data in the hope that the use of an increased number of measurements would ultimately increase the amount of relevant information obtained, these approaches do not deal directly with the underlying theoretical problems.

Several alternative approaches which purportedly circumvent the theoretical shortcomings of conventional cephalometric analysis[10-20] have been used primarily to describe shape changes over time. Less attention has been given to their use in classifying patterns at a given point in time. One

Abstract

Elliptical Fourier functions (EFF) were generated for the boundary outlines of the hard tissue craniofacial complex including the maxilla, mandible, and cranial base in order to quantitatively describe adult patients (n=98) who were initially classified into nine skeletal groups by a combination of conventional cephalometric measures and clinical judgement. The mean residual fit of the EFF-predicted points and the original digitized data for the individual subjects ranged from .42 mm to .61 mm with a mean of .52 mm suggesting an accurate fit. Visual inspection of the individual plots confirmed this. Predicted classifications from a step-wise discriminant analysis based on EFF amplitudes were compared with the original classifications. The discordance rates for A-P and vertical plane classification were 21% and 13% respectively with an overall discordance rate of 33%. In general, a cluster analysis using EFF amplitudes did not identify clusters very similar in membership to the original groups; however, it was marginally successful in identifying members of the more severe groups and, like discriminant analysis, appeared to be more sensitive to vertical morphological differences. The overall lack of agreement between classifications and clusters based on EFF amplitudes and the original classifications may indicate that traditional skeletal categories such as those used in this study do not actually represent discrete groups.

Key Words

Elliptical Fourier functions • Skeletal jaw relationships • Orthodontic classification

Submitted: June 1993 **Revised and accepted for publication:** December 1993 Angle Orthod 1994;64(4)299-310

Table 1
Cephalometric values used for initial classification.

	Class II	Class I	Class III
A-B difference (mm)			
Vertical based on:			
1. NHP			
2. FN	>8	1 < Class1 < 6	< -1
3. SN rotated			
	Short	**Normal**	**Long**
% Nasal Ht	≥ .47	.43 ≤ N ≤ .45	≤ .42
SN/MP (degrees)	< 29	29 ≤ N ≤ 37	> 37
LFH (mm)			
-Male	< 68	68 < N < 74	< 76
-Female	< 63	64 < N < 70	>72

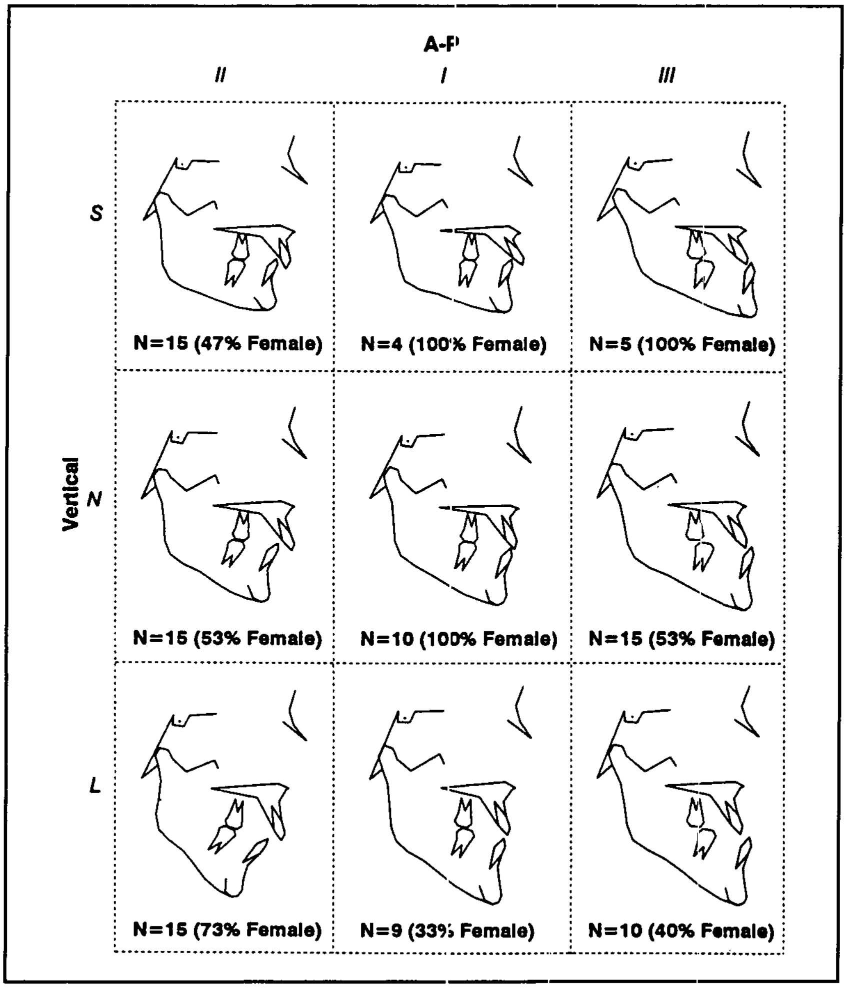

Figure 1
Composite tracings of the nine skeletal groups.

of these alternative approaches is the elliptical Fourier function technique (EFF) which, like conventional harmonic analysis, is a curve-fitting procedure that is based on the strategy of imbedding a set of closely spaced measurements on an outline or boundary of a form into a mathematical function.[5,21] Conventional Fourier descriptors and EFF's have been used successfully to map complex morphological forms including the human cranial vault,[22] cranial base,[23,24] and mandible.[25] Lu[26] suggested that Fourier coefficients could be used in a discriminant function to classify different facial types, and recently Fourier descriptors have been used in conjunction with multivariate analyses to evaluate skeletal jaw relationships[27] and soft tissue profiles.[28]

The purpose of this project was to evaluate the ability of elliptical Fourier functions and derived harmonic amplitudes to quantitatively describe and classify normal and extreme facial patterns.

Materials and methods

Lateral cephalometric radiographs of 676 adults (males and females ≥ 15 years old) were evaluated using six traditional cephalometric skeletal measures. Subjects were initially classified in the anteroposterior (A-P) plane as skeletal Class I, II, or III and vertically as short, normal, or long face using the measures and cutoff values given in Table 1. These were based on available normative data[1,29-31] and clinical experience.

The A-B horizontal difference was chosen as the A-P measure because it best approximates how patients are viewed in real life.[31,32] Since some cephalograms were not taken in natural head position, three vertical reference lines ("true" vertical based on natural head position, vertical relative to Frankfort horizontal, and vertical relative to sella-nasion rotated 6 degrees) were used to measure the A-B horizontal difference. The three vertical measures chosen had been selected as significant predictors in a discriminant function analysis to classify patients with extreme vertical problems in a previous study.[8] These vertical measures represent three distinct types of cephalometric measures: angular (SN/MP), linear (LFH), and ratio (% nasal ht.).

Subjects were eligible if at least two of the A-P and two of the vertical classifications agreed and if the clinical impression of a trained clinician agreed with both the A-P and vertical classifications. Since the intent of the study was to differentiate among extreme facial forms, a conscious effort was made to exclude all borderline cases so that nine discrete groups (three A-P by three vertical) could be established with each group represent-

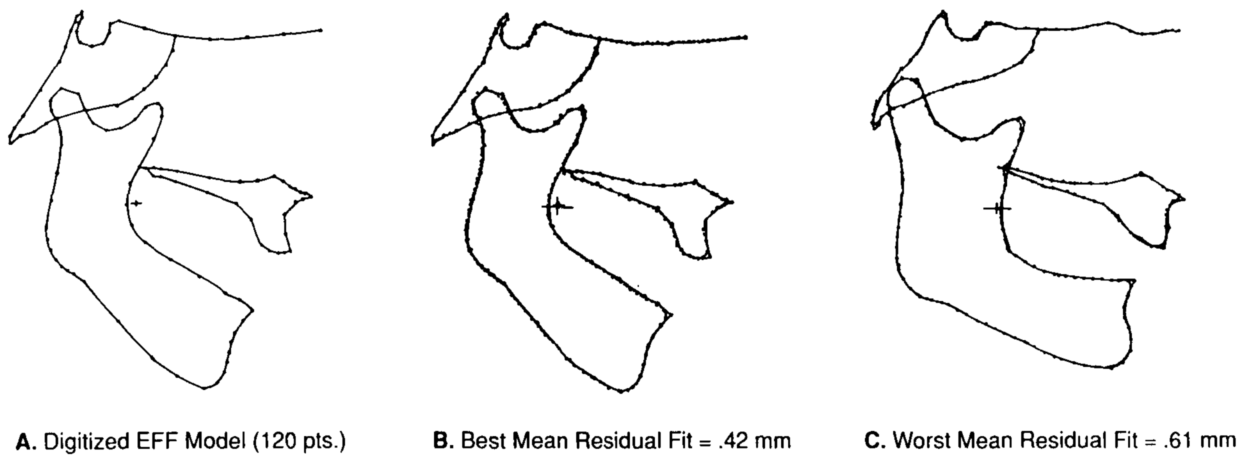

Figure 2

Figure 2A-C
A, Digitized 120-point EFF model. B, Superimposition of the digitized (solid) and EFF computed (dotted) outlines for the patient with the best mean residual fit. C, Superimposition as in B for patient with the worst mean residual fit.

ing a unique facial configuration possessing a different combination of A-P and vertical skeletal jaw relationships. This classification approach is taken from earlier works by Sassouni[33] and Sassouni and Nanda[34] in which the importance of A-P/vertical interactions was stressed. Patients were assigned to each of the nine groups until 15 patients had been selected for a given group or until all the subjects meeting the cephalometric and clinical criteria for that group had been evaluated. Based on this protocol, 98 subjects were selected for Fourier description and classification. A composite tracing, representing the averaged facial form for each of the nine groups, along with the demographics of each group are shown in Figure 1.

The cephalometric radiographs of the 98 patients were traced and digitized for EFF analysis according to a 120-point model that represented the boundary outline of the craniofacial complex including the maxilla, mandible and cranial base (see Figure 2A). This model included 34 conventional cephalometric (CCA) landmarks that are frequently used in cephalometric analyses and 86 other points spaced at defined intervals between these landmarks. All tracings were oriented along sella-nasion for comparison purposes, and a scaling factor based on the area bounded by the outlines was used to correct for differences in size. The measurement error for the 34 CCA landmarks was calculated from three replicated tracings of 10 radiographs. Measurement error ranged from .35 mm (nasion) to 1.96 mm (the most inferior point on the mandibular border with respect to the mandibular plane). Measurement error was not calculated for the remaining points since their locations were dependent upon the CCA points.

The boundary outlines were fitted with elliptical Fourier functions with 50 harmonics using a specially written routine in POWER BASIC as described by Lestrel.[20] The predicted points (i.e. expected values) were computed to test the goodness-of-fit of the functions to the originally observed data points and were then plotted to provide a visual display of the data. Figures 2B and 2C demonstrate the best and worst fits respectively between the original digitized tracings and the EFF predicted points outlines.

The x and y amplitudes of each harmonic were computed for each individual subject. The mean, standard deviation, and percent contribution of the mean x and y amplitudes for each harmonic were calculated for each of the nine groups. Percent contribution represents the percentage that the mean amplitude of each harmonic contributed to the overall EFF function. The mean amplitudes for the first 13 harmonics are illustrated for the four most extreme groups (Class II/short, Class II/long, Class III/short and Class III/long) in Figure 3. The Fourier series was truncated at the 13th harmonic because the percent contribution for higher degree amplitudes (14-50) was negligible. No mean amplitude past the 13th harmonic contributed more than 1% to the total function and the first 13 harmonics contributed approximately 90% of the total (Table 2).

Figure 3
Mean amplitudes plotted against harmonics for the four most severe skeletal classification groups.

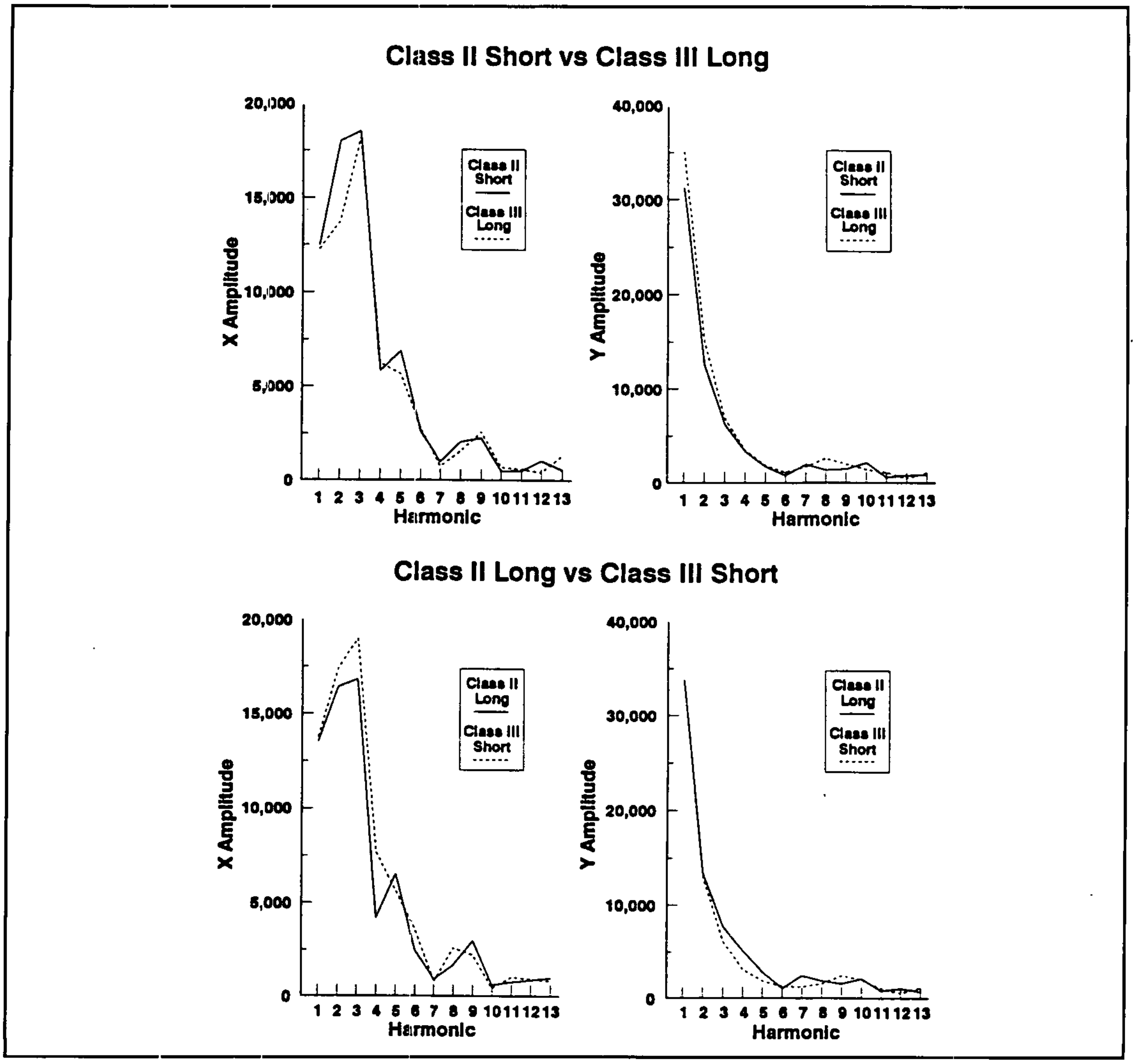

Figure 3

Univariate analysis of variance was performed first on each of the 26 amplitudes (13 x and 13 y) with the A-P classification, vertical classification, and the interaction between A-P and vertical classifications as predictors. The interaction between the A-P and vertical dimensions was significant ($P < 0.05$) for 11 of the 26 amplitudes indicating that the A-P and vertical dimensions are not independent of one another in their effects on the amplitudes and that the A-P and vertical dimensions should not be considered separate effects in the discriminant analysis.

Since some of the 26 amplitudes may be redundant, a step-wise discriminant analysis was performed to determine the smallest set of amplitudes required to find the multivariate linear discrimination function which would best differentiate the nine skeletal groups. Amplitudes were included in the model if the p-value to enter was .10 or less and to stay was .05 or less. Each subject was classified as a member of one of the nine groups on the basis of the function derived from the amplitudes identified by the step-wise analysis. The classification probability was calculated using the cross validation method[35] by applying the functions to the data from which they were generated. The decision to truncate at 13 harmonics/26 amplitudes was supported by the fact that a discriminant analysis using all 50 harmonics/100 amplitudes did not significantly improve the agreement between discriminant function and original classifications.

Average-linkage cluster analysis was also performed using the 26 amplitudes in an agglomerative hierarchical clustering procedure. Average-linkage cluster analysis was used because this method tends to perform better on average than other methods.[35] Each observation was initially considered a cluster by itself and clusters were joined if the pseudo t^2 statistic calculated for the average linkage distance was 10 or less. Even though cluster analysis often identifies outliers and small clusters which should not be interpreted as classification groups, the mini-

Table 2
Percent contribution of the mean X and Y amplitudes for the first 13 harmonics

Harmonic #	Mean X Amplitude % contribution	Mean Y Amplitude % contribution
1	16.37	42.28
2	21.20	17.28
3	23.73	8.57
4	7.56	4.69
5	8.24	2.68
6	3.68	1.22
7	1.16	2.36
8	2.57	2.29
9	3.17	2.40
10	0.73	2.63
11	0.86	0.99
12	1.13	1.02
13	1.12	1.24
Total	91.52	89.65

Table 3
The amplitudes selected by the step-wise discriminant analysis. The proportion of variability (R^2) in the amplitude selected at each step is that variability explained by the linear discrimination among groups and covariates entered on previous steps.

Step	Amplitude Entered	Amplitude Removed	Number In	Partial R^2
1	X2		1	0.537
2	Y4		2	0.527
3	Y1		3	0.388
4	Y11		4	0.317
5	X6		5	0.284
6	X1		6	0.376
7	X5		7	0.276
8		Y1	6	0.091
9	Y2		7	0.244
10	X8		8	0.270
11	X4		9	0.256

Table 4
Absolute and relative frequencies of subjects classified into the nine skeletal groups

Original Group Classification	Discriminant Analysis Classification Agree N	Agree %	Disagree N	Disagree %
Long				
Class I, N=9	6	66.7	3	33.3
Class II, N = 15	13	86.7	2	13.3
Class III, N = 10	8	80.0	2	20.0
Normal				
Class I, N = 10	5	50.0	5	50.0
Class II, N = 15	10	66.7	5	33.3
Class III, N = 15	10	66.7	5	33.3
Short				
Class I,N = 4	2	50.0	2	50.0
Class II, N = 15	11	73.3	4	26.7
Class III, N = 5	3	60.0	2	40.0
Total	**68**	**66.7**	**30**	**33.3**

Table 5
Summary of the discordances in the anteroposterior and vertical planes

Original Group Classification	Discriminant Analysis Classification		
Anteroposterior	Class II	Class I	Class III
Class II (n=7)		6	1
Class I (n=10)	6		4
Class III (n=4)		4	

Original Group Classification	Discriminant Analysis Classification		
Vertical	Short	Normal	Long
Short (n=3)		3	
Normal (n=6)	3		3
Long (n=4)		4	

mum cluster size was set at three since two of the original groups had five or fewer members.[35,36]

Results

Predicted points were computed from EFF's for each individual subject to test the goodness-of-fit of the function to the original observed data. The mean residual fit of individual subjects ranged from .42 mm to .61 mm with a mean of .52 mm suggesting an accurate fit between the original digitized outlines and the EFF predicted outlines (Figures 2B and 2C). Visual inspection of both the original and predicted plots suggested that most of the intergroup variability was located in the shape and position of the mandible (Figure 1).

Ten amplitudes (6 x and 4 y) were selected by the step-wise discriminant analysis as the best set of amplitudes to differentiate the nine skeletal groups (Table 3). The y amplitude of the first harmonic was initially entered as step 3 but was then subsequently removed in step 8. The absolute and rela-

Figure 4
Cluster membership graphed with respect to original classification. Each individual is represented by one number. The numbers correspond to the cluster numbers and cell location defines the original classification. The exact locations within each cell and the enclosures for each cluster are arbitrarily drawn for visual purposes.

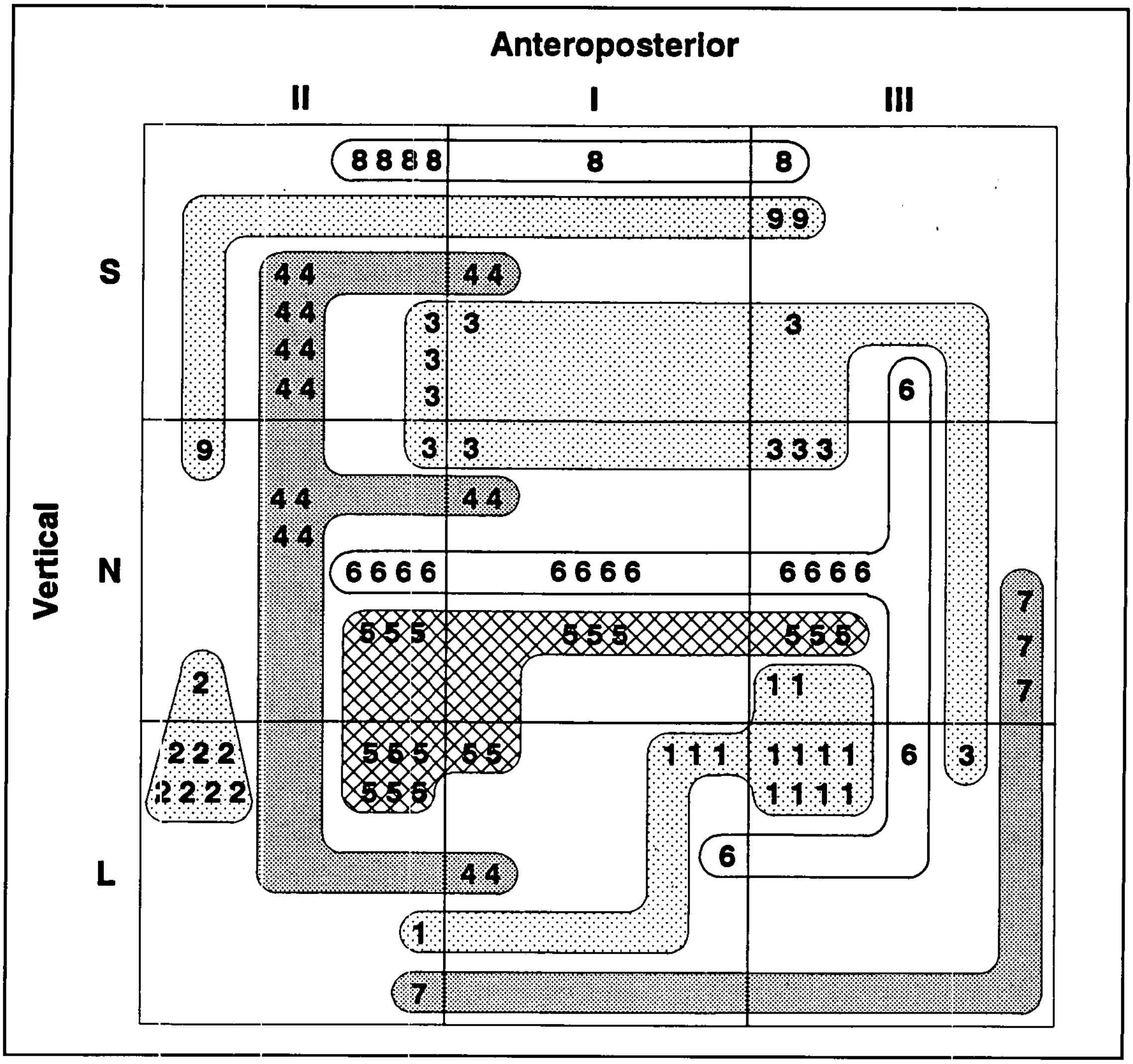

Figure 4

tive frequencies of agreement and disagreement between the predicted and original group classifications are given in Table 4. For 68 of 98 subjects, approximately two-thirds of the sample, the predicted group classification was the same as the original classifications in both planes of space. The classifications were discordant in both the A-P and vertical planes of space for only four of the remaining 30 subjects; 17 disagreed solely in the A-P plane and nine solely in the vertical plane. Thus, the discordance rates for A-P and vertical plane classification were 21% and 13% respectively with an overall discordance rate of 33%. In general, the discordances were evenly distributed (Table 5). For example, of the 10 "Class I" discordances, six were classified as Class II and four as Class III and of the six "normal" discordances, three were classified as long and three as short. One subject who was classified originally as a Class II was classified as Class III by the discriminant analysis. This was the only major clinical discordance noted.

The cluster analysis results identified 96 subjects as belonging to nine clusters with each cluster having at least three members. The two patients who remained as independent clusters were assumed to be outliers and were excluded from further consideration. Figure 4 shows the relationship between the memberships in the nine clusters and the original group classifications. In the vertical plane of space, the vast majority of shorts (21 out of 24) fell into clusters three, four and eight while most of the longs (29 out of 33) were in clusters one, two or five. A similar differentiation among the A-P categories was not as evident.

In considering simultaneous (A-P and vertical) classification, the cluster analysis was marginally successful in aggregating subjects in three of the four most severe original classification groups: Class II/short, Class III/long and Class II/long; there were too few subjects in the Class III/short group to adequately assess. For example, eight of the 14 cluster one members were Class III /longs and five of the other six were in bordering groups-Class III/normal or Class I/long; using the original classifications, eight out of 10 Class III/longs were in cluster one. Seven out of eight cluster two members were Class II/longs while seven of the 15 Class II/longs were in cluster two. Eight out of 18 cluster four members were Class II/shorts and six of the remaining 10 were in bordering groups-Class I/short or Class II/normal. From the original classifications, eight out of 15 Class II/shorts were in cluster four.

Discussion

The Fourier approach has, as its main advantages over CCA, the ability to measure complex forms accurately as well as the ability to control for differences in size, thus facilitating comparison based solely on shape.[19] EFF accurately described the boundary outline encompassing the cranial base, maxilla and mandible of the 98 subjects in this study. The mean residual fit and visual inspection of EFF plots superimposed on the original outlines both confirm this. In addition, because EFF allows for the simultaneous evaluation of the A-P and vertical planes in two dimensions, it should be able to capture many of the subtle A-P/vertical interactions unique to the craniofacial complex. The question remains whether the practitioner and/or researcher can successfully use these mathematical descriptions for classification purposes.

The discriminant function results suggest that classification based on EFF amplitudes was marginally in agreement with the original classifications. The vertical classification discordance rate of only 13% was quite good, but the overall error rate of 33% was high and probably points to the inherent difficulty in simultaneously evaluating two planes of space. Only four extreme discordances (i.e. disagreeing in both A-P and vertical planes of space) were noted representing only 4% of the total sample. In addition, only one instance of a major clinical discordance (i.e. classifying a II as a III) was noted. Nevertheless, low frequencies of major discordances were expected given the intentional sampling biases imposed and the fact that the predicted group classification was generated by applying the functions to the same data from which the functions were generated. If the functions were applied to a new sample of patients the discordance rates would almost certainly be higher.

Cluster analysis results were more difficult to interpret. The cluster analysis did aggregate the majority of the members in some of the more severe groups and, like discriminant analysis, appeared to be more sensitive to vertical morphology. Overall, however, the clusters were not very similar in membership to the original groups. Apparently, the analysis was aggregating subjects based on criteria different than that used to make the original and/or discriminant analysis classifications. The apparent increased sensitivity of both the discriminant and cluster analyses to vertical differences may simply reflect that the original classification system was more sensitive to vertical morphology and/or less sensitive to A-P differences.

The overall lack of agreement between classifications and clusters based on EFF amplitudes and the original classifications may be interpreted in several ways. It may be that more, or at least different, information is needed to improve upon the agreement. The decision-making process in clinical judgement undoubtedly involves differential variable weighting. Correct classification might have been improved if the appropriate values for such weights were known and could be included as a priori information. Using Fourier coefficients as data rather than amplitudes and/or eliminating the size standardization procedure, and thereby allowing size to be used as part of the discrimination, are two potential ways to increase the amount and/or type of information available. It is also possible that the inclusion of phase angle information might have led to better agreement between the new and original classifications. On the other hand, the elaborate 120 point/50 harmonic model may actually have yielded too much information which "muddied the water". For example, most of the visual differences in these patients appears to be located in the shape and position of the mandible. Combining all three structures into one may have allowed the similarities in the cranial base and maxilla to obscure the more significant differences that apparently exist in the mandible. One potential solution would be to break down the overall model into separate models representing the three component parts. EFF's could be computed for each of the three component structures and discriminant analysis and/or cluster analysis performed on the pooled variables.

Ferrario and coworkers[27,28] have also found substantial differences between Fourier-based and conventional classification methods. They suggest that Fourier analysis results in more accurate classification standards because it allows for a more comprehensive evaluation of the form in question. While this may be true, substantiation is difficult since there is no definitive criteria (i.e. no true gold standard) upon which to judge success. Nevertheless, it is possible that cluster memberships based on the EFF amplitudes are indeed more "correct" than the original classifications. In other words, the lack of agreement between the classification based on EFF and the original memberships may actually reflect problems inherent with the initial classification system rather than with the EFF technique.

Patients in this study were initially classified to represent the "discrete" groups that clinicians often talk about and, in many cases, use as a basis for treatment. However, it is possible that clinicians, in their efforts to reduce the continuum that actually represents facial form into simplified groups, are actually overlooking subtle but important morphological interactions and, thus, are really only defining hybrid groups as opposed to real, discrete entities. Even given the intentional sampling biases designed to decrease the variability in this study, it seems that there is still enough variability in the data to obscure the perceived clinical differences. The lack of agreement between classifications and clusters based on EFF amplitudes and the original classifications may indicate that the EFF data are providing new and important information that, having been historically overlooked, will ultimately lead to different and more accurate systems of classification. Because of these possibilities, placement of patients into skeletal categories such as those originally used in this study should be viewed with caution, especially if treatment decisions are to be based on those categorizations.

Summary and conclusions

The following conclusions can be drawn from this study:

1. Elliptical Fourier functions can provide accurate mathematical descriptions of complex craniofacial outlines.

2. Using a resubstitution method, predicted classifications from a step-wise discriminant analysis based on EFF amplitudes agreed with 67% of the original classifications in both the A-P and vertical planes of space. Only four of the 30 disagreements were discordances in both A-P and vertical dimensions. The better sensitivity to vertical morphology probably reflects that the original classification system was more sensitive to vertical morphology in the first place.

3. Cluster analysis of the EFF amplitudes did not identify clusters very similar in membership to the original groups; however, this analysis was margin-

ally successful in identifying members of the more extreme groups and, like discriminant analysis, appeared to be more sensitive to vertical morphological differences.

4. Possibilities to improve upon the EFF classification and its agreement with the original classifications exist and have been discussed. However, it is quite possible that in reality the problem may lie with the original classification system rather than with the EFF technique. The EFF data may well be providing new and important information that, having been historically overlooked, will ultimately lead to different and more accurate systems of classification.

Placement of patients into traditional clinical categories and basing treatment decisions upon these memberships should be viewed with caution.

Acknowledgments

The authors wish to thank Debbie Price, Kyle Harrison, and Sonja Davis for their excellent technical support. This paper supported in part by NIH Grant DE-08708 and DE-05215 from the National Institute of Dental Research.

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Commentary: Skeletal jaw relationships

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Cephalometrics in orthodontic practice is an established diagnostic tool employed by clinicians worldwide. Conventional cephalometrics has served orthodontic research and diagnosis since its standardization in 1931.[1] It is only in recent times that conventional cephalometric analysis has become the subject of increased scientific scrutiny.

The orthodontic literature is replete with different analyses based upon linear, angular and/or proportional measurement systems. When applied to cephalometrics, these systems have little rigorous theoretical backing and are based mainly upon convention.[2] In fact, in six decades of cephalometric usage, there has been relatively little scientific progress in the measurement of cephalometric form or in the measurement of biological form in general.

The problem areas in cephalometrics can be divided into the following:

1.) Imaging difficulties: the reduction of a complex three-dimensional craniofacial form into a two-dimensional projection is the first in a cascade of steps which results in the indiscriminate loss of information in cephalometry.

2.) Datum point selection: in conventional cephalometics irregular two-dimensional form is reduced to a handful of datum points. Limited numbers of datum points provide only a cursory description of craniofacial form, yielding no data concerning the curvature of boundary outlines,[3] resulting in further indiscriminate data loss.

3) Measurement difficulties: the combination of the loss of the third dimension and further reduction of data through the use of limited datum point arrays is compounded by their summarization through inappropriate measurement techniques.

Linear and angular techniques or their respective ratios are inadequate for describing cephalometric form.[4] Different combinations of datum points may produce the same angle[5] or linear distance.

Also, size and shape parameters cannot be discriminated from traditional linear and/or angular cephalometric dimensions. Thus a change in the facial angle or distance between gonion and condylion may reflect a size or shape change, or more likely varying combinations of size and shape changes.

Conventional cephalometric analysis generally involves a univariate approach of comparing individual measurements with corresponding population means. This method is more appropriate for population studies than for individuals.[6] In addition, the variable correlation between different conventional cephalometric measures renders them unsuitable for univariate statistical analysis.[7] Multivariate techniques are better suited to cephalometric analysis and allow comparison of an array of measurements as a whole as opposed to discrete parts.

In addition, the use of multiple discrete measurements in conventional cephalometrics depends on their subjective analysis. It is difficult, if not impossible, for a clinician to recount the logical steps made in arriving at a cephalometric diagnosis from the array of measurements which make up a conventional analysis.[8]

If traditional cephalometrics is fraught with so many problems, how has it been possible for cephalometrics to produce any useful results?

Conventional cephalometric measurements are probably correlated with more sophisticated forms of measurement to a greater or lesser degree. For example, a patient with a large mandible (even if differently shaped than a "normal" mandible) is likely to show increases in most linear measurements of the mandible. Similarly, a "long face" is usually associated with an increased vertical dimension.

Dr. Lowe and coworkers have addressed the concerns about conventional cephalometrics by using a measurement technique (EFF) with a rigorous scientific basis well-suited to the task of measuring irregular biological forms. As opposed to the Finite Element Method (FEM, a different rigorously-based method of measuring biological form) EFF facilitates the measurement of outline form. They then analyzed the EFF data appropriately using multivariate statistical techniques.

The difficulty with EFF (and FEM) is that its parameters are difficult to understand (when compared with the relatively simple conventional cephalometric measures). For example, we can all picture how the mandibular plane angle will change as the mandible rotates open. What will happen to EFF parameters in this scenario? At the present time we simply do not have enough knowledge to elucidate how EFF parameters might vary to reflect different skeletal morphological patterns.

One could argue that multivariate analysis will take care of this uncertainty. However, it is important that the multivariate analysis be provided with appropriate variables that reflect the important data. For example, measurements of cranial base form are likely to be less important in orthodontic A-P skeletal diagnosis than those of maxillo-mandibular form. This factor can be taken into account by the differential variable weighting, which can reduce misclassification in Cluster analysis.[9-11] In fact, the decision to include or exclude a variable is in itself a form of weighting.

This paper has taken steps to address fundamental problems in cephalometrics. This could lead to further research which will provide for more formal diagnostic techniques and therefore more logical objective treatment planning.

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