Modeling Facial Movement: I. A Dynamic Analysis of Differences Based on Skeletal Characteristics

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Purpose: To introduce a novel approach to analyze and model facial movements; and to quantify variations in facial movement caused by the extent of skeletal differences between the maxilla and mandible and the middle to lower facial heights. The hypothesis was that there are differences in facial movement related to the underlying facial skeleton which may be explained by the shape of the face rather than the pattern of movement.

Patients and Methods: The study sample consisted of 43 subjects (23 men, 20 women) with a mean age of 18.5 years (SD = 11.90). Measures of the facial skeletal differences were made from lateral cephalometric radiographs, and subjects were classified as Class I and Class II, and normal to decreased lower anterior face height, respectively. Facial movements were recorded by a video-based tracking system. Descriptive and inferential statistics were performed on principal component scores generated from the movement data. A linear mixed-effects model was used to test for significant differences in movement among the different skeletal types.

Results: A dynamic modeling of facial movements was described that has numerous potential clinical applications. Also, differences in movement were found during the lip purse movement. Specifically, skeletal Class I individuals showed greater forward and upward movement during lip purse compared with individuals with severe skeletal Class II who moved their lips straight forward with less magnitude of movement.

Conclusion: For most of the movements, apart from the lip purse, differences in motion were explained by static facial shape.

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Dentofacial deformities are the result of extreme variations in skeletal morphology that affect facial appearance, facial balance, and function. Orthognathic surgery for dentofacial patients has successfully improved the dental and facial form in these patients, but functional outcomes have been less frequently studied. Those aspects of the pre- and postsurgical function that deserve further attention include masticatory ability, neurosensory recovery, and facial animation or movement. Past reports and clinical impressions suggest that subjects with severe facial dysmorphology have distortions of facial movement.[1] These distortions may not only impact external perceptions of facial esthetics during animated behaviors such as smiling and eating, but also may have important implications for postsurgical stability and retention. Unfortunately, research in facial animation has been limited by a lack of appropriate measures.

In previous studies, we quantified facial movements in normal adults[1,2] and in patients with cleft lip and palate.[3] These analyses were based on a measurement of maximum displacement of discrete facial landmarks,[1,3] and on the relative changes of the distances between the landmarks.[4] The topic of this research builds on past studies in our laboratory and focuses on the following question: Do subjects have quantifiable differences in facial movement that vary by the type and extent of dentofacial dysmorphology? The specific aims of this study were as follows: 1) to introduce a novel approach to statistically analyze and model facial movement data in which differences in movement are described in

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FIGURE 1. Camera configuration and set-up for recording facial movements.

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terms of complete dynamic motion rather than static summary measures at 1 time point; and 2) to quantify variations in facial movement caused by the type and extent of different skeletal characteristics specifically related to differences between the maxilla and mandible, and differences between the middle to lower facial heights. The hypothesis was that there are differences in facial movement which are related to the underlying facial skeleton, and these differences can be partially or totally explained by the shape of the facial skeleton.

Patients and Methods

The study sample consisted of 43 subjects (23 men, 20 women) with a mean age of 18.5 years (SD = 11.90) recruited from patients attending the University of North Carolina School of Dentistry Orthodontic and Dentofacial Clinics (Chapel Hill, NC). Inclusion criteria were a willingness to participate in the study and the availability of a lateral cephalometric radiograph at least 3 months before the facial movement data collection. Exclusion criteria were a diagnosis of a known craniofacial anomaly; a diagnosis of facial impairment; and the presence of facial hair that would interfere with facial landmark placement. Approval for the study was obtained from the Institutional Review Board at the University of North Carolina and informed consent was obtained from each subject before data collection.

Measures of maxillomandibular and middle-lower facial skeletal differences were made from the lateral cephalometric radiographs. The extent of any maxillomandibular *skeletal* difference was measured by the ANB angle.[5] Subjects were classified as Class I and Class II based on the following: skeletal Class I, $0° \leq$ ANB angle $\leq 5°$; and skeletal Class II, ANB angle $> 5°$. The final number of subjects that fell in each ANB skeletal category were Class I = 22 and Class II = 21. The range of variation for the ANB angle was 0.5° to 12°. The extent of the middle-lower facial *skeletal* difference was measured by the ratio of the middle to lower face (MF/LF).[5] Subjects were classified as normal and low based on the following: normal, $0.5 \leq$ MF/LF ≤ 1.0; and low, MF/LF > 1.0. The final number of subjects that fell in the normal and low categories was 8 and 37, respectively. The range of variation for the MF/LF ratio was 0.64 to 1.61.

RECORDING CIRCUMORAL MOVEMENTS

A video-based tracking system (Motion Analysis; Motion Analysis Corporation, Santa Rosa, CA) was used to measure the circumoral movements of each subject. This system tracks retro-reflective markers secured to specific facial landmarks (Fig 1). The movement of each marker was captured in real time by the tracking system. Four analog video cameras with lenses of 25 mm focal length were positioned in front of the subject to record the spatial positions of the markers at a rate of 60 frames/sec for 3 seconds. To obtain 3-dimensional coordinate data for a marker, 2 cameras must record the marker position in space.

Because markers on the face may be carried outside the field of view of the 2 primary cameras, 2 additional cameras were used to ensure that data from at least 2 cameras were recorded for all facial markers.

Before recording facial movements of each subject, the space within which the head was positioned was first calibrated. This calibration was completed with a cube-shaped metal space frame (20 cm on each edge) fitted with an array of 12 markers; and a 21.5-cm long wand fitted with 3 markers, 1 marker on each end, and 1 marker 4.5 cm from 1 end (Dimensional Inspection Laboratories [Fremont, CA] had previously certified the position in space of the markers to an accuracy of ± 7.6 nm). Lens distortion was corrected automatically. Under conditions of the study, lens distortion as determined by a 3-cm object positioned at the center and corners of the measurement space produced a mean error of 0.53 mm (± 0.45).

Twenty-four spherical retro-reflective markers, each with a diameter of 2 mm, were attached by means of eyelash adhesive to specific sites on the facial skin of each subject (Fig 2). Each subject was then positioned within the calibrated measurement field, and instructed to make 7 *maximum* facial animations from rest: smile, lip purse (kissing movement), cheek puff, grimace, eye opening, eye closure, and mouth opening. For the instructed smile, the patient was asked to "bite on his/her back teeth" and to "smile as much as possible and then relax." Recent work showed that the instructed maximum smile was very similar in characteristics to the natural smile.[2] The inclusion of the other animations served to complete the range of movements expected in the lower facial regions during expressive behavior. Before data collection, all animations were practiced with each subject. Then, 3 trials of each animation were recorded for each subject at the same sitting.

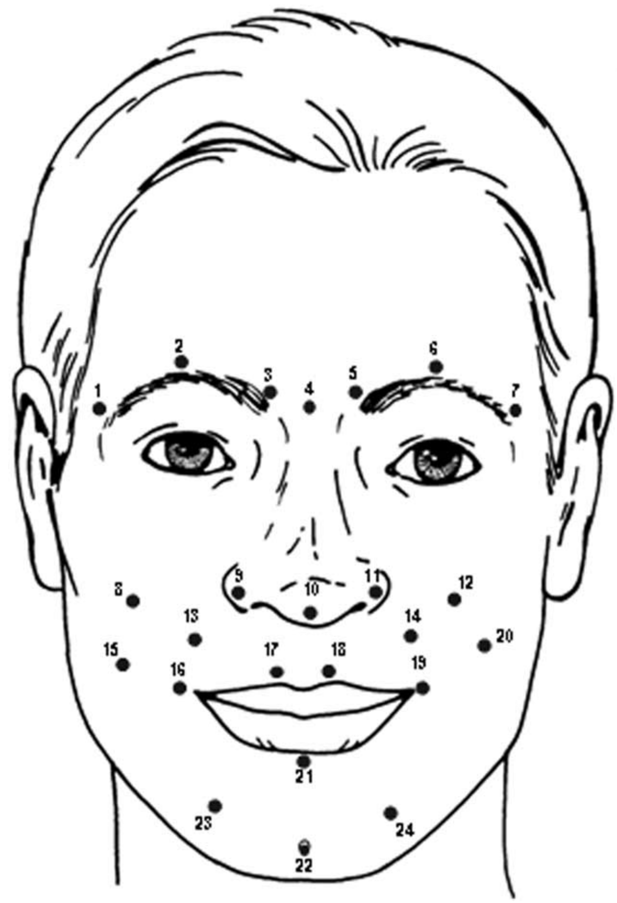

FIGURE 2. Facial landmark location. 1 & 7, right and left lateralciliary points located above most lateral aspect of eyebrows; 2 & 6, right and left superciliary points located above most superior aspect of eyebrows; 3 & 5, right and left interciliary points located above medial aspect of eyebrows; 4, midnose point located on midline of nasal bridge in line with medial canthi; 8 & 12, right and left maxillary points located on cheek one quarter distance between right and left ala and right and left temporomandibular joint, respectively; 9 & 11, right and left lateral alar points located on lateral alar rims; 10, nasal tip point located on nasal tip; 13 & 14, right and left nasolabial points located on nasolabial fold, midway between right and left ala and commissures, respectively; 15 & 20, right and left cheek points located on cheek one quarter distance between right and left commissures and temporomandibular joints, respectively; 16 & 19, right and left commissure points located on commissures; 17 & 18, right and left upper lip points located on peaks of Cupid's bow; 21, mid-lower lip point; 22, midchin point located 2 cm below point 21; 23 & 24, right and left chin points located 2 cm lateral to point 22 and 2 cm below points 16 and 18, respectively.

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DATA PROCESSING

In the examples in Exhibit 1, differences caused by head motion and timing of movement by the same person are shown. (See Appendix for a description of how to obtain and operate the viewing software to review the exhibits referred to in this article. It is important to view the motion from the side as well as the front.) Consider the smile movement in which there are 2 smiles of the same person. Three important characteristics of the data are displayed: 1) Because head motion was not restricted, the initial positions of the subject's head in each smile were not exactly aligned; 2) Both smiles occurred over different lengths of time during the 3-second period, that is 1 subject may have completed the smile movement quickly within 3 seconds while another subject may have used the entire time; and 3) A small amount of noise caused by measurement error was visible as the movements were made. These errors were obvious on toggling through the movements in Exhibit 1. Differences caused by head motion were particularly obvious for the smile movement, while errors caused by timing were obvious for the lip purse and mouth opening movements. To model the average facial movements and conduct further analyses of these data, these errors were removed as described below.

Shape Description

From a statistical perspective, the configuration of 24 landmarks on the facial soft tissue constituted a shape,[6,7] and this static facial form of the face differed among individuals in the study (eg, skeletal Class I vs Class II individuals). However, the focus of this study was not on the static facial form, but rather on how the soft tissue, overlying the facial form, changed when facial movements were made. Thus, the intent was to measure movement independent of the static form. Therefore, new analytical techniques were developed to model these movements.

These techniques were based on the change in distances between pairs of facial landmarks. Let $d_{ij}(t)$ be the distance between landmarks i and j at time t. Then, let $r_{ij}(t) = (d_{ij}(t)/(d_{ij}(0))-1$ represent the relative change in the distance from rest. This measure has several desirable properties:

- It is invariant to whole head motion.
- Because of the relative scaling, it is approximately invariant to small variations in the placement of markers on facial landmarks.
- It is not dependent on local shape. For example, consider the distance between the commissures (ie, landmark nos. 16 and 19). In some individuals this distance will be larger because they have wider mouths; however, the focus is not on this distance "at rest" but on how it changes during movement (eg, a smile). By scaling to the initial at rest distance, much of the local form is removed.

Lele and Richtsmeier[8] reported on an approach to statistical shape analysis called Euclidean distance matrix analysis. This analysis was based on overall pairs of distances. Given the matrix, it is possible to reconstruct the shape. The important difference between Lele and Richtsmeier's analysis and the one presented here is that in this analysis not all pairs of distances are needed to reconstruct the shape. In their analysis, given n landmarks, there are $n(n-1)/2$ pairs of distances, and for an n of any size, this number of pairwise distances is substantial and increasingly cumbersome for the types of analyses demonstrated in this study. For example, in this study with an $n = 24$, there are a total of 276 pairwise distances for just a single frame of 1 movement.

Reconstruction of the Face

Given only a subset of pairwise distances, the face can be reconstructed in the following manner (Fig 3):

- Four landmarks are chosen. These landmarks are connected with 6 pairwise distances. With these 6 distances, the position of the landmarks can be reconstructed up to rotation and translation. Of the 2 possible reflections, the correct one can be chosen given previous knowledge of the relative positions of these landmarks on the face. The translation is irrelevant and the rotation, although arbitrary, can be chosen to place the face in an upright position for viewing.
- A new landmark is then chosen, and the 3 pairwise distances of this landmark to the landmarks that were previously positioned are obtained. Based on the 1 new landmark and 3 old landmark distances, the (irregular) tetrahedron can be reconstructed. Two possible tetrahedra satisfy the distance requirements; however, knowledge of the general shape of the face is used to select the correct one.
- New landmarks are added in the same manner until the face is complete.

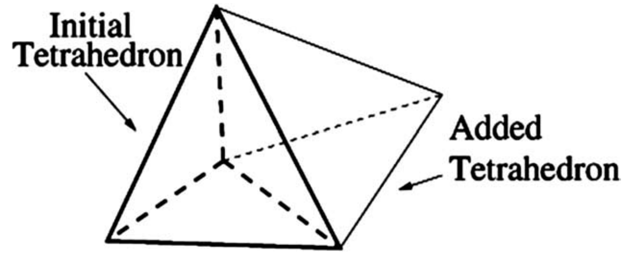

FIGURE 3. Six distances are required to construct the initial tetrahedron. Three additional distances are required to place each subsequent tetrahedron.

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The particular order of reconstruction is important and is chosen to ensure a stable reconstruction under the range of conditions observed in these data. This method requires only $3n-6$ pairwise distances. For $n = 24$, this means that only 66 pairwise distances need to be considered versus 276 in Lele and Richtsmeier's analysis.[8]

Registration of Animations

The subjects were instructed to perform a particular movement from the "rest" position. For example, for the smile movement, the motion started from the neutral rest position and moved to a maximum position of the smile, and then relaxed to a rest position (Fig 4). The movement was completed within 3 seconds. Five phases to the movement were recognized:

- 'At rest' phase
- Movement phase to the maximum position
- Holding phase at maximum position

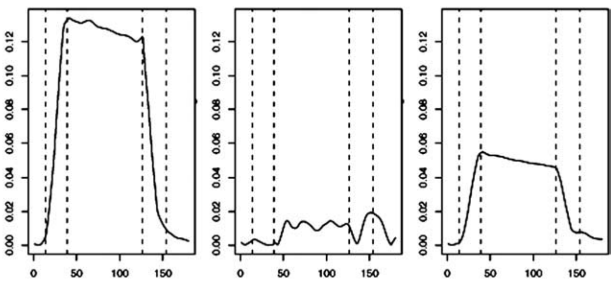

FIGURE 4. Selected relative change from rest for a smile. *Left*, 13 to 17 (upper lip). *Center*, 4 to 5 (eyebrow). *Right*, average of 66 pairwise distances. Transitions selected are shown.

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- Relaxation movement phase from the maximum position
- 'At rest' phase

These 5 phases result in 4 transition times that will vary from movement to movement. Therefore, it is important to ensure the following: movements are not averaged cross-sectionally; movements must be "registered" with each other so that comparable points in the movement are averaged; and the transition times must be precisely identified, a procedure that is difficult.

These issues are illustrated in Figure 4. Information from a smile is depicted. The first panel in Figure 4 shows a smoothed $r_{13,17}(t)$, which represents the distance between landmark nos. 13 and 17 on the upper lip. The 5 phases of this distance during the movement are clearly identifiable, although the transitions are somewhat imprecise. The center panel in Figure 4 shows $r_{4,5}(t)$, which represents the distance between landmark nos. 4 and 5 above the eye. In this case the phases are not identifiable. As might be expected, this distance does not show much movement during a smile because most of this movement is confined to the lower part of the face. It is clear that to choose the transitions, the plot in the first panel would be preferred.

Unfortunately, these patterns differ among animations and among individuals, and a pairwise distance that is appropriate to select the transitions for 1 movement might be different for another movement. Therefore, the average $r_{ij}(t)$ over all 66 pairwise distances, as shown in the right panel, was used to select the transitions. These transitions were identified manually by 1 investigator (J.F.). Also, this investigator was blinded to the data to avoid bias in the transition selections. Manual selection also allowed the detection of aberrant measures that then were corrected or excluded.

B-Spline Representation

To model the curves shown in Figure 4, standard cubic B-splines were used. The angle curves were represented as linear combinations of the following basis functions, $B_j(t)$ for $j = 1, K, m$. The ith curve is represented as

$$r_i(t) = \sum_{j=1}^{m} R_{ij}B_j(t) + \varepsilon(t)$$

where the coefficients R_{ij} are found by minimizing a least-squares criterion

$$\int_0^1 (r_i(t) - \sum_{j=1}^{m} R_{ij}B_j(t))^2 dt$$

The particular B-spline basis was determined by the choice of knot location. The knots were evenly spaced within the 5 phases described previously. Furthermore, because it is known that $r_i(0) = r_i(end) = 0$, this restriction could be imposed directly by omitting the first and last B-spline basis functions. The B-spline basis functions with just 1 interior knot for each phase that corresponded to Figure 4 are shown in Figure 5. Because the transition points differed among the movements, the placement of the knots were also different; however, the statistics R_{ij} on the coefficients were compared and computed with the assurance that R_{i1j} and R_{i2j} represented the same part of the movement. The positions of the knots ensured appropriate registrations of the curves. An m of 16 was chosen which allowed for 6 knots at the endpoints and transitions, and 2 interior knots in the phases.

Statistics

For convenience, the matrix R_{ij} was unrolled into a vector R_k where $k = 1, K, m(3n-6)$ represented 1 complete movement. For an $m = 16$ and $n = 24$, the result is a vector of length 1,056. Also, the distance between the landmarks at rest, $d_{ij}(0)$, was unrolled into a vector d_k where $k = 1, K, (3n-6)$ represented the face at rest. Then, to reconstruct the whole movement, $d_{ij}(t) = d_{ij}(0)(1 + R_{ij}(t))$ was computed.

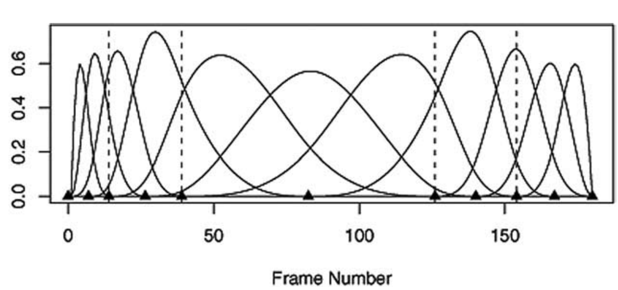

FIGURE 5. B-spline basis functions corresponding to transitions in Figure 3. Knot locations are shown on the horizontal axis. Note the zero values at the 2 endpoints.

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Means

Means for each of the 6 movements were calculated within different subgroups of the data. For example, the average smile was calculated on the average face of all the subjects by averaging R_k and d_k over all the smiles. To calculate this smile movement as well as the other movements, the timing of the 4 transitions had to be specified. The means of the transitions were calculated, but for ease of comparison between different displays, these transitions were set at $t=1/6, 2/6, 4/6, 5/6$. An example of this average smile, as well as the other movements, is shown in Exhibit 2.

It is not necessary to use the same subgroups for the calculation of the movement and the static face. Thus, $d_{ij}(t) = d^A_{ij}(0)(1 + R^B_{ij}(t))$ could be calculated where A and B represent means computed over different groups of individuals or even just a single individual. For example, an individual's smile could be imposed on his or her own face or alternatively, any movement could be imposed on any face. This particular application of the present technique would be useful for displaying the normal movement of a patient. Also, the effects of static shape and dynamic motion could be decomposed. For example, an assessment might be made of whether a particular subgroup differed from another because the movement or form was different, or because both the movement and form were different. To illustrate this concept, consider 2 subgroups of subjects based on the MF/LF score. One group consisted of subjects with normal and the other with high MF/LF scores, the latter indicating a lower anterior facial height.

Exhibit 3 shows a comparison of the average movements of normal MF/LF subjects on the average of this group's own face with the average movements of the subjects with low anterior facial heights on the average of this lower face height group's own face. There are clear differences in the sizes of the 2 average faces and in the movement; however, it is unknown whether these differences are because the high MF/LF group has a different facial form (static size and/or shape) or because the particular movement is different. In Exhibit 4, a comparison was made of the average movements of the normal MF/LF subjects on the average of the normal face with the average movements of the subjects with high MF/LF on the average of the *normal* face. Because the movements are superimposed on the same standard face, the differences observed now are caused by just the particular movement, and these differences appear less substantial. Exhibits 5 and 6 show these same comparisons for the subjects with normal and high ANB angles.

Variance

There is substantial natural variation in facial movement. The nature of this variation over all the subjects can be described with a principal components analysis on the R_k. In this case, there are 1,056 variables, but if any 1 movement is considered, for example the smile, then counting all the smiles separately, there are only 145 cases. Nevertheless, the principal components can be calculated. The percentage of variation explained by the first 5 components are 32.9%, 11.1%, 6.8%, 5.7%, and 5.0% (Table 1), respectively, and $\bar{R} \pm 2\sqrt{s_i}v_i$ is calculated where s_i and v_i are the ith eigenvalue and eigenvector, respectively. Exhibit 7 shows the direction of movement of the first principal component for each movement (eg, smile, lip purse, and so on), and is a comparison of the average plus 2 SD of movement superimposed on the average face with the average −2 SD of movement also superimposed on the average face.

Table 1. PERCENTAGE (%) VARIATION IN MOVEMENT EXPLAINED BY PRINCIPAL COMPONENTS 1 TO 5

	Percentage (%) Explained Variance				
	Principal Components				
Animations	1	2	3	4	5
Smile	32.90	11.07	6.80	5.68	4.93
Lip purse	25.21	13.24	7.53	5.85	4.72
Cheek puff	17.54	14.61	9.86	7.42	5.60
Grimace	17.79	14.92	9.76	7.22	5.14
Eye closure	36.79	8.41	6.56	5.11	4.21
Eye opening	28.90	13.17	10.41	5.76	4.86
Mouth opening	51.61	7.26	4.82	4.33	3.90

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Inference

The standard techniques of multivariate analysis[9] could have been applied to this analysis; however, because of the large dimension (1,056 in our example), the power of such tests would be inadequate and unimportant differences between the groups would be detected. Instead, the inferences were performed on the first few principal component scores. In Figure 6, the first 3 principal component scores were plotted against MF/LF. No relationship was apparent in the plots, although some groupings of the 3 replicates per subject were seen. A linear mixed-effects model for the jth replicate of subject I was fitted:

$$pc_{ij} = \beta_0 + \beta_1 MFLF_i + \gamma_i + \varepsilon_{ij}$$

where γ_i was the random subject effect with variance σ^2_γ, while within-subject variation ϵ_{ij} had variance σ^2_ε. The same model was fitted for the ANB angle. Within-subject consistency in movement was assessed by the intraclass correlation coefficients for the first 3 principal component scores: intraclass correlation coefficients = (σ^2 among subjects)/(σ^2 among subjects + σ^2 error).

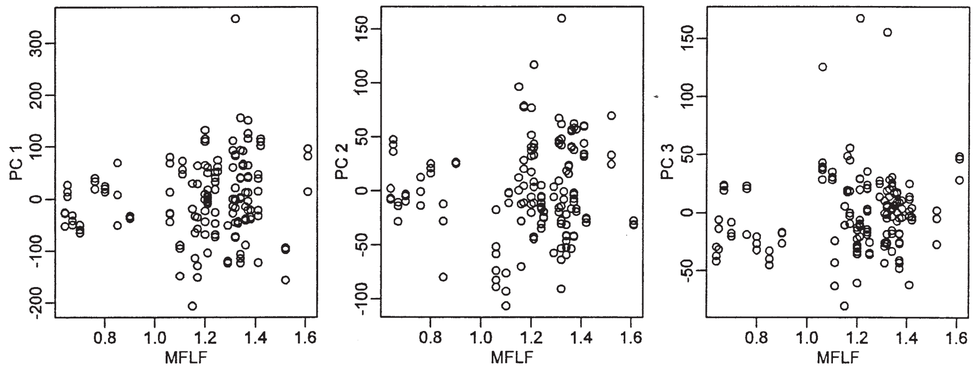

FIGURE 6. First 3 principal components of the smile against MF/LF.

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Results

The results for the comparisons of the average movements superimposed on the average face of the group with normal facial height compared with the average movements of the low MF/LF group superimposed on the average face of the group with normal face height are shown in Exhibit 4. The corresponding results for the comparison of the group with normal range ANB angle and the group with high ANB angle are shown in Exhibit 6. Thus, Exhibits 4 and 6 show the movements once the faces were scaled to the same size. Table 1 gives the percentage of the variation explained by the first 5 principal components. It can be seen that the first 2 principal components explain most of the variation.

The results of the linear mixed-effects model (Tables 2 and 3) show that only the first principal component for the ANB angle during the lip purse movement was significant (P = .0003). The results for the intraclass correlation coefficients (Table 4) showed that the first principal component was more consistent than the second and third. For the first principal component, mouth opening was the most consistent movement, followed in order by grimace, eye closure, cheek puff, lip purse, eye opening, and smile; for the second principal component the order was eye opening, grimace, eye closure, mouth opening, smile, cheek puff, and lip purse; and for the third principal component, the order was grimace, cheek puff, eye opening, lip purse, smile, eye closure, and mouth opening.

Discussion

In this study a unique statistical approach for modeling facial movements was presented. Because interpretation of movement data is difficult when based on the numerical data only, this new holistic, dynamic, and visual representation offers a significant advance over current comparative analyses. The new analysis allows for the isolation of facial movements and the superimposition on a 'neutral' face, so that only the true movement can be compared and the effects of different facial profiles, shapes, and sizes can be removed. Additionally, the superimposition of movement can be on any face, so that an individual's average movement also can be displayed on his or her own face. The current analysis is based on principal component scores, which are useful to identify unusual movements, and so, can be used to detect faulty or exceptional movements. Furthermore, to provide a quantitative measure of abnormality, the scores can be used to rate a patients' impairment in

Table 2. LINEAR MIXED EFFECTS MODEL FOR THE MFLF VARIABLE: RESULTS OF SIGNIFICANT PRINCIPAL COMPONENTS

	MFLF Ratio		
	P Values for Principal Component		
Animations	1	2	3
Smile	0.3729	0.7245	0.2816
Lip purse	0.1103	0.2531	0.2393
Cheek puff	0.0718	0.5988	0.2797
Grimace	0.7786	0.7689	0.3651
Eye closure	0.7131	0.9911	0.3446
Eye opening	0.4132	0.7359	0.1923
Mouth opening	0.4062	0.4891	0.3307

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Table 3. LINEAR MIXED EFFECTS MODEL FOR THE ANB VARIABLE: RESULTS OF SIGNIFICANT PRINCIPAL COMPONENTS

	ANB Angle		
	Principal Component *P* Values		
Animations	1	2	3
Smile	0.7048	0.6416	0.8220
Lip purse	0.0003	0.2660	0.1339
Cheek puff	0.8487	0.0326	0.9074
Grimace	0.3538	0.7094	0.3971
Eye closure	0.2852	0.9961	0.5654
Eye opening	0.5108	0.8629	0.8460
Mouth opening	0.9646	0.1140	0.7647

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Table 4. INTRACLASS CORRELATION COEFFICIENTS FOR THE PRINCIPAL COMPONENT SCORES 1, 2, AND 3 OF EACH MOVEMENT

	ICC		
	Principal Component *P* Values		
Animations	1	2	3
Smile	0.61	0.69	0.42
Lip purse	0.74	0.41	0.52
Cheekpuff	0.75	0.48	0.64
Grimace	0.87	0.85	0.75
Eye closure	0.85	0.80	0.22
Eye opening	0.70	0.86	0.57
Mouth opening	0.90	0.74	0.21

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movement with respect to the movement of a control group, and also to provide an objective assessment of differences in movements among different skeletal types and changes caused by surgery.

Soft tissue movements of the circumoral region that reflected activity of the lip, nasolabial, chin, and cheek regions were the focus of the analysis. The within-subject variance in movement indicated that while there was some consistency in the movements for each animation, there was also a fair amount of variation. Thus, an observer might have difficulty detecting differences from just looking at an individual at a single time-point, a finding that supports the use of a more sensitive method to assess movement differences as described in this study.

The differences in movement because of the skeletal characteristics, as measured by the ANB angle and the MF/LF ratio, were minimal once the movements were superimposed on a standard face, eliminating the effects of skeletal differences. Thus, the results of this study may support the hypothesis that differences in facial movement could be partially or totally explained by the underlying facial skeleton. In practice, a standardization and normalization of the facial hard and soft tissue is achieved by orthognathic surgical procedures. Our general findings imply that, provided there is no prior impairment in movement, once the skeletal facial form is normalized, facial movement should be more normal as well; however, statistically these findings may be altered by increasing the sample size, and therefore, must be interpreted with caution.

An exception to this finding was the lip purse animation. In this instance, the skeletal Class I and skeletal Class II subjects showed differences in facial movement even after superimposing the movement on a neutral face. The modeling of the lip purse movement suggested that individuals with skeletal Class I had greater forward and upward movement of the lips when making the movement, while those with a severe skeletal Class II moved the lips straight forward with less magnitude of movement (Exhibit 6). Both the direction and magnitude of the movement was limited for skeletal Class II subjects, suggesting that the soft tissue movement may not have been able to compensate for the underlying skeletal discrepancy during the lip purse movement.

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Appendix

To review the exhibits referred to in this article, a viewer has been constructed to display the facial movements at any angle. The viewer may be downloaded from http://www.stat.lsa.umich.edu/~faraway/face/. The viewer keyboard commands are the following:

- Function keys F1 through F5 – Load Exhibit 1 through 5, respectively.
- Arrow keys rotate the view.
- a – Shows first (or only) face movement.
- b – Shows second (if available) face movement.
- c – Shows both (if available) faces moving.
- Shift < or shift > – Increases or decreases the face size.