Sensitivity of a Method for the Analysis of Facial Mobility. I. Vector of Displacement

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Objective: **(1) To determine which facial landmarks show the greatest movement during specific facial animations and (2) to determine the sensitivity of our instrument in using these landmarks to detect putatively abnormal facial movements.**

Design: **Movements of an array of skin-based landmarks on five healthy human subjects (2 men and 3 women; mean age, 27.6 years; range, 26 to 29 years) were observed during the execution of specific facial animations. To investigate the instrument sensitivity, we analyzed facial movements during maximal smile animations in six patients with different types of functional problems. In parallel, a panel was asked to view video recordings of the patients and to rate the degree of motor impairment. Comparisons were made between the panel scores and those of the measurement instrument.**

Results: **Specific regions of the face display movement that is representative of specific animations. During the smile animation, landmarks on the mid- and lower facial regions demonstrated the greatest movement. A similar pattern of movement was seen during the cheek puff animation, except that the infraorbital and chin regions demonstrated minimal movement. For the grimace and eye closure animations, the upper, mid-facial, and upper-lip regions exhibited the greatest movement. During eye opening, the upper and mid-facial regions, excluding the upper lip and cheek, moved the most, and during lip purse, markers on the mid- and lower face demonstrated the most movement. We used the smile-sensitive landmarks to evaluate individuals with functional impairment and found good agreement between instrument rankings based on the data from these landmarks and the panel rankings.**

Conclusion: **The present method of three-dimensional tracking has the potential to detect and characterize a range of clinically significant functional deficits.**

KEY WORDS: *facial animation, three-dimensional, Mahalanobis*

Orthodontists are concerned with both form and function in the habilitation of patients with facial anomalies and clefts. However, in the past, outcomes have been analyzed from static measurements of facial form. Dynamic studies of soft-tissue movement are limited. Clearly, a quantification of the movements that occur during facial function can serve as a vital outcome measure of surgical success. Several workers in other fields have analyzed facial movement (LeResche and Dworkin, 1988; Neely et al., 1992; Johnson et al., 1994; Jousif et al., 1994; Paletz et al., 1994; Wood et al., 1994; Morrant and Shaw, 1996; Bajaj-Luthra et al., 1997; Johns et al., 1997), and a few have used instruments that provide a three-dimensional measurement of facial motion with promising results (Frey et al., 1994; Gross et al., 1996; Trotman et al., 1996; Cacou et al., 1997).

In a previous manuscript (Trotman et al., 1998), we investigated the error associated with, and demonstrated the utility of, one such instrument designed to measure facial movement. Our present study builds on this research and focuses on the issue of sensitivity. The purpose of this study was to determine which regions of the face show the greatest movement during specific facial animations, and then to use landmarks in these regions to determine the sensitivity of this instrument in detecting putatively abnormal facial movements.

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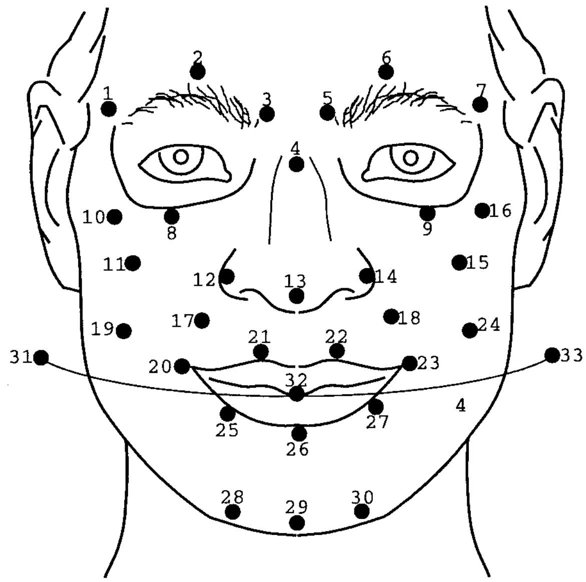

FIGURE 1 **Facial landmarks. 1 and 7: Right and left lateralciliary points located above the most lateral aspect of the eyebrow. 2 and 6: Right and left supraciliary points located above the most superior aspect of the eyebrow. 3 and 5: Right and left interciliary points located above the medial aspect of the eyebrow. 4: Midnose point located on the midline of the nasal bridge in line with the medial canthi. 8 and 9: Right and left infraorbital points located on the infraorbital notch. 10 and 16: Right and left zygomatic points located on the outer orbital region equidistant below the lateral canthi as points 1 and 7 are above. 11 and 15: Right and left maxillary points located on the cheek ¼ of the distance between the right and left alar and right and left TMJ, respectively. 12 and 14: Right and left lateral alar points located on the lateral alar rims. 13: Nasal tip. 17 and 18: Right and left nasolabial points located midway between the right and left alar rims and the right and left commissure, respectively. 19 and 24: Right and left cheek points located on the cheek ¼ of the distance between the right and left commissure and right and left TMJ points, respectively. 20 and 23: Right and left commissure points located on the commissure. 21 and 22: Right and left upper-lip points located on the peak of Cupid's bow. 26: Mid-lower-lip point located on the lower lip vermillion. 25 and 27: Right and left lower-lip points located on the lower lip midway between points 20 and 26 and points 23 and 26, respectively. 29: Midchin point located 2 cm below point 26. 28 and 30: Right and left chin points located 2 cm on either side of landmark 29 and 2 cm from points 25 and 27 on the lower-lip vermillion border.**

METHODS

A video-based tracking system (Motion Analysis™, Motion Analysis Corporation, Santa Rosa, CA) served as the basis of the present assessment of facial motion. Thirty-three spherical retroreflective markers, each with a diameter of 4 mm, were attached to the facial skin and maxillary dentition (Fig. 1). Four analog video cameras recorded these markers at a sampling rate of 60 frames per second (Fig. 2). Under ideal conditions, only two cameras are necessary to track a marker in three dimensions; however, two additional cameras served as backups in case the markers showed inadequate spatial separation or were carried outside the field of view of the primary cameras. Light meter readings indicated 175 lux of daylight in the area of interest. Data obtained by the four cameras were recorded in real time on four analog video recorders for later off-line digitization and processing. Camera optics consisted of lenses with a focal length of 25 mm. Prior to each recording session, the space within which the subject's head was to be positioned was calibrated with a cube-shaped metal space frame (200 mm on each edge) fitted with an array of 12 markers whose positions in space were certified to an accuracy of $\pm$7.6 nm by Dimensional Inspection Laboratories (Fremont, CA).

TABLE 1 **Patient Characteristics**

Patient	*Facial Anomaly*	*Gender*	*Age (years)*
1	Right facial paralysis	Female	20
2	Repaired bilateral cleft lip and palate	Male	17
3	Facial trauma	Female	10
4	Repaired right unilateral cleft lip and palate	Male	17
5	Repaired bilateral cleft lip and palate	Male	17
6	Repaired right unilateral cleft lip and palate	Male	11

Each subject then was positioned with his or her head within the calibrated measurement field. Lens distortion was corrected by means of a translation table provided with each of the lenses, and high-definition resolution enhancement techniques were employed on a frame-by-frame basis. Residual distortion was determined by analyzing repeated measurements of a 3-cm test object positioned at the center and corners of the measurement space. The mean error was 0.53 mm (SD = 0.45 mm). The position of each marker on the patient's face was referenced to the calibration cube, and a tracking algorithm that used a target search area of 0.9 nm in diameter was used to estimate the spatial position of each marker. Computations were executed by a computer workstation (Sun Sparc™, Sun Corporation, Palo Alto, CA). Off-line digitization of the video data was effected one data stream at a time. Channels were synchronized by timing cues stored on all four analog tapes. Each frame was digitized at a horizontal and vertical resolution of 245 x 245 pixels. Data for each of the markers were stored on hard disk for subsequent analysis.

Subjects

Informed consent was obtained from all participants in this study. In order to identify regions of the face that are most mobile during specific facial animations, five healthy human subjects (2 men and 3 women; mean age, 27.6 years; range, 26 to 29 years) were studied. In each of these subjects, we investigated the movement of an array of skin-based markers (Fig. 1) during the execution of six facial animations (Fig. 3): (1) smile, (2) lip purse, (3) cheek puff, (4) eye closure, (5) eye opening, and (6) grimace. All animations were repeated three times by each subject. Because the head was unrestrained, its movement had to be estimated and subtracted from that of the markers used to detect facial movement.

To estimate head movement, presumably stable dental markers were employed. A maxillary acrylic splint with an attached facebow was fabricated for each subject. The facebow arms

FIGURE 2 Camera arrangement and measurement area.

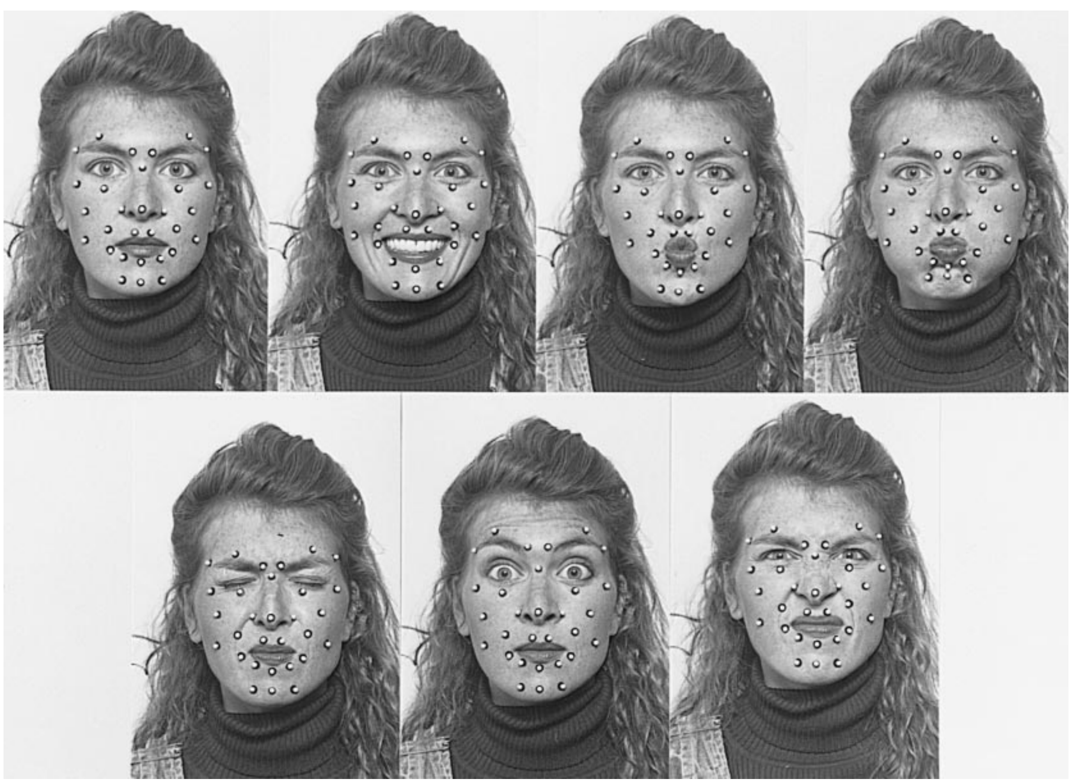

FIGURE 3 Facial positions. Rest, smile, lip purse, cheek puff, eye closure, eye opening, and grimace.

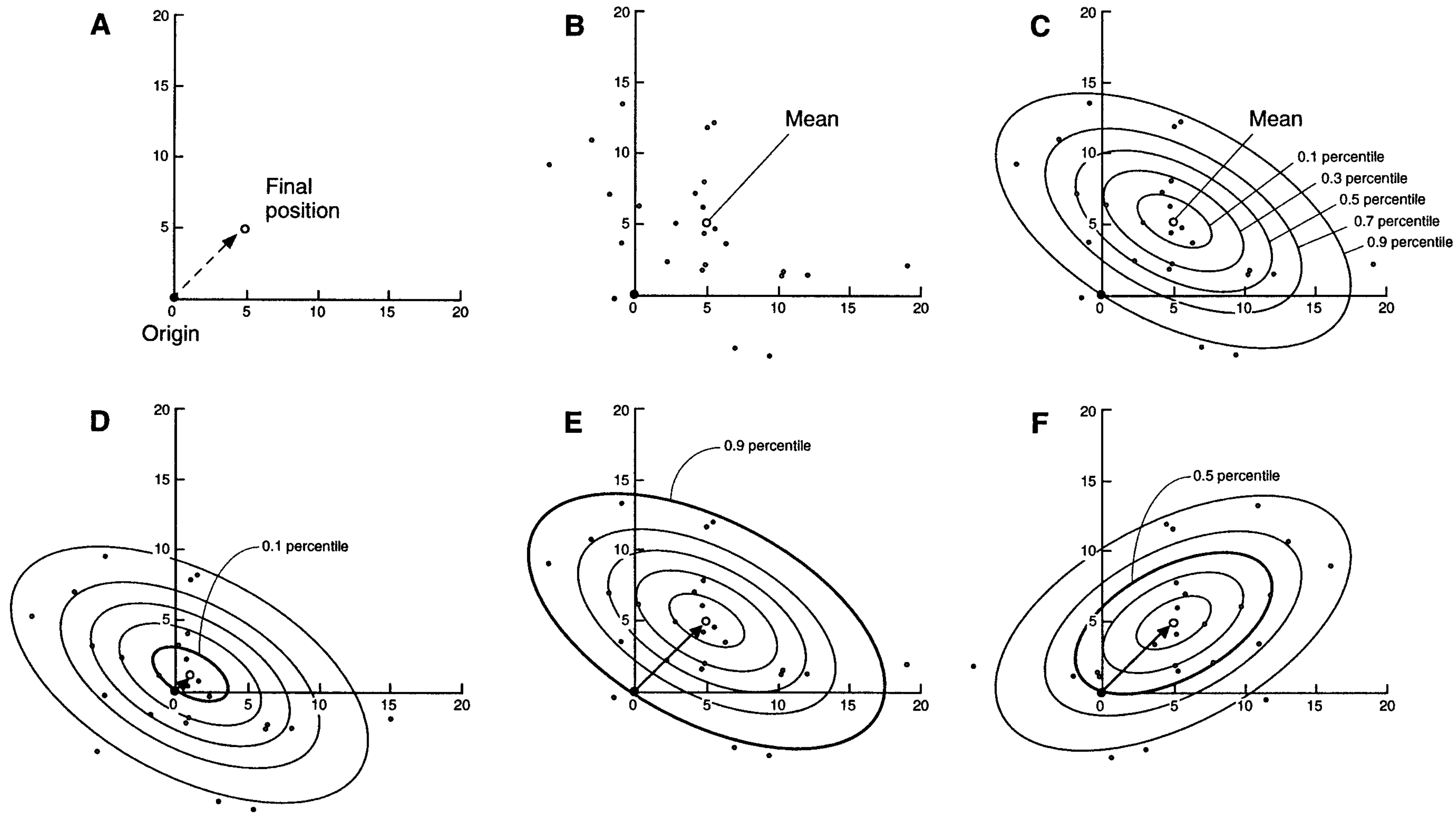

FIGURE 4 Schematic representation of Mahalanobis distances. A: Consider a marker that is displaced during an animation from its initial position to a final position of maximum displacement. B: On repeated animations, the same markers will produce a "cloud" of final displacement positions having a mean shown by an open circle. C: Based on their mean and covariances, we can compute percentiles, represented by the plain line ellipses, to represent the distribution of these displacements. D: A measure of the mean movement of the marker from the origin would be the percentile whose ellipse passes through the origin. The marker shown here has a score of 0.10 (10th percentile). The score implies little consistent movement away from the origin on repeated animations for this marker. E: Marker with a Mahalanobis score of 0.90 (90th percentile). The score of 0.90 represents a clear, consistent pattern of movement away from the origin. F: This marker has the same mean millimetric displacement as the marker in 2E; however, the marker in 2F has a lower Mahalanobis score (0.50) because of the differences in orientation of the distribution (ellipses) compared to 2E. These figures are two-dimensional representations of three-dimensional computations.

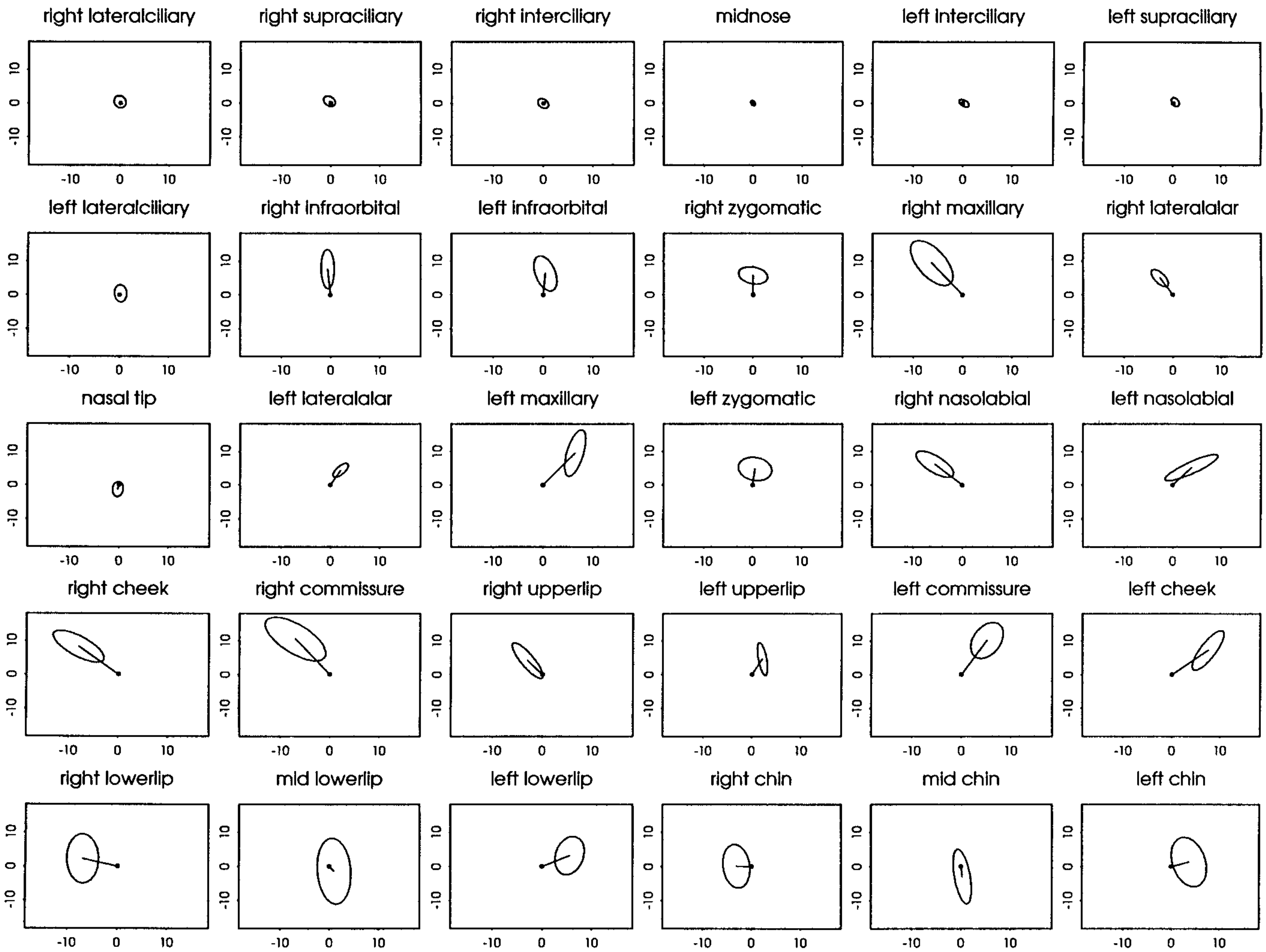

FIGURE 5 Schematic representation of the frontal two-dimensional vectors (looking directly at the subject's face) for markers of the normal subjects during the smile animations. The origins of these plots (small dark circles) represent the initial relaxed position. The small clear circles represent the positions of markers at maximum displacement. The ellipses represent the estimated 95th percentile of displacement based on the assumption of normality, and we estimate that 95% of the population would lie within or on these ellipses. The greatest movements occur for landmarks on the mid- and lower face, and especially for those landmarks on the circumoral region.

were bent clear of the lips. Three markers then were attached to the facebow (and thus indirectly to the dentition) as shown in Figure 1.

To investigate the sensitivity of this instrumentation in detecting probable functional deficits, we analyzed facial movements during maximal smile animations in six patients with different forms of congenital and acquired functional problems (Table 1). Because these problems involved the mouth, we limited our analysis to the movements of the five markers in the circumoral region that moved the most during smiling (Figs. 1 and 3 markers 20, 21, 22, 23, and 26). The animation was repeated three times by each patient.

To control for among-subjects size differences, the distances between the right and left commissure points of all subjects and patients were scaled to a common length. The mean intercommissure width at rest was calculated for the five normal adult subjects. For each patient, the intercommissure width at each point in time then was multiplied by the ratio of the mean width for the adults to the mean intercommissure width for the patient. This scaling was necessary because variation in marker displacement in different patients could reflect differences in face size, with larger faces showing greater displacement, thereby confounding the measurement of movement.

A panel of five orthodontic residents was asked to view video recordings of the patients executing the smiles and then rate the degree of motor impairment. Each rating was made on a 100-mm visual analog scale anchored on the left by "no perceived facial motion problems" and on the right by "severe perceived facial motion problems." The five panelists rated the patients a second time at the same sitting, but with the order of the patients rerandomized. Comparisons then were made between the mean panel scores for each patient and those of the motion analysis system.

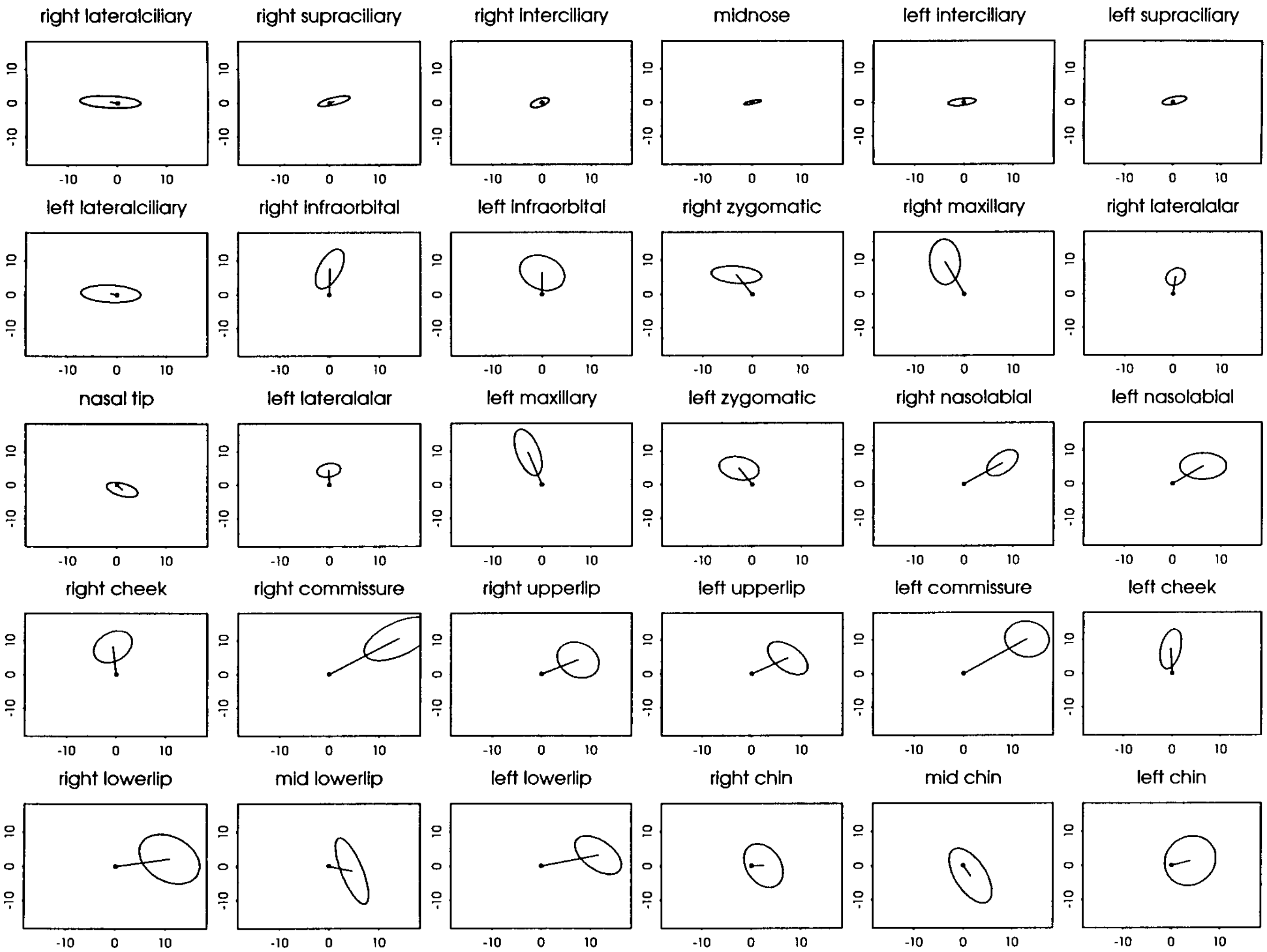

FIGURE 6 Schematic representation of the sagittal two-dimensional vectors (looking at the left side of the subject's face) for markers of the normal subjects during smile animations (as in Figure 3). The greatest movements occur for landmarks on the mid- and lower face, and especially for those landmarks on the circumoral region.

Data Analysis and Statistics

Marker Sensitivity to Movement

The movement of each marker from the initial relaxed position was calculated with respect to the calibrated space frame. To describe the movement of the facial markers relative to the head, the coordinates of the centroid of the three, presumably stable, dentition-supported markers then was subtracted from that of each of the skin-based markers to give an estimate of facial movement during a given animation. For each marker, the three-dimensional coordinates at the point of maximum displacement relative to the origin or rest position were calculated. These vectors of displacement then were described in terms of Mahalanobis scores or percentiles.

Given a cluster of points (in this instance, marker displacement), the Mahalanobis score or percentile describes the relative displacement of a point from the center of the cluster. This displacement is scaled by the nature of the scatter along the direction of the displacement. To explain further, consider a marker that is displaced during an animation from its initial "rest" position (origin) to a position of maximum displacement, as depicted in Figure 4A. On repeated animations, the same marker will produce a "cloud" of final displacement positions having a mean shown in Figure 4B. Based on the mean and covariances, we can represent the distribution of the displacements by computing percentiles taking the form of plain line ellipses in Figure 4C. A measure of the mean movement of the marker from the origin would be the percentile whose ellipse passes through the origin. Figure 4D and 4E demonstrates two markers with Mahalanobis scores of 0.10 and 0.90 (10th and 90th percentiles), respectively. In the case of the marker in Figure 4D, the score implies little consistent movement away from the origin on repeated animations for this marker. For the marker at the 90th percentile of displacement shown in Figure 4E, the score of 0.90 therefore represents a clear, consistent pattern of movement away from the origin.

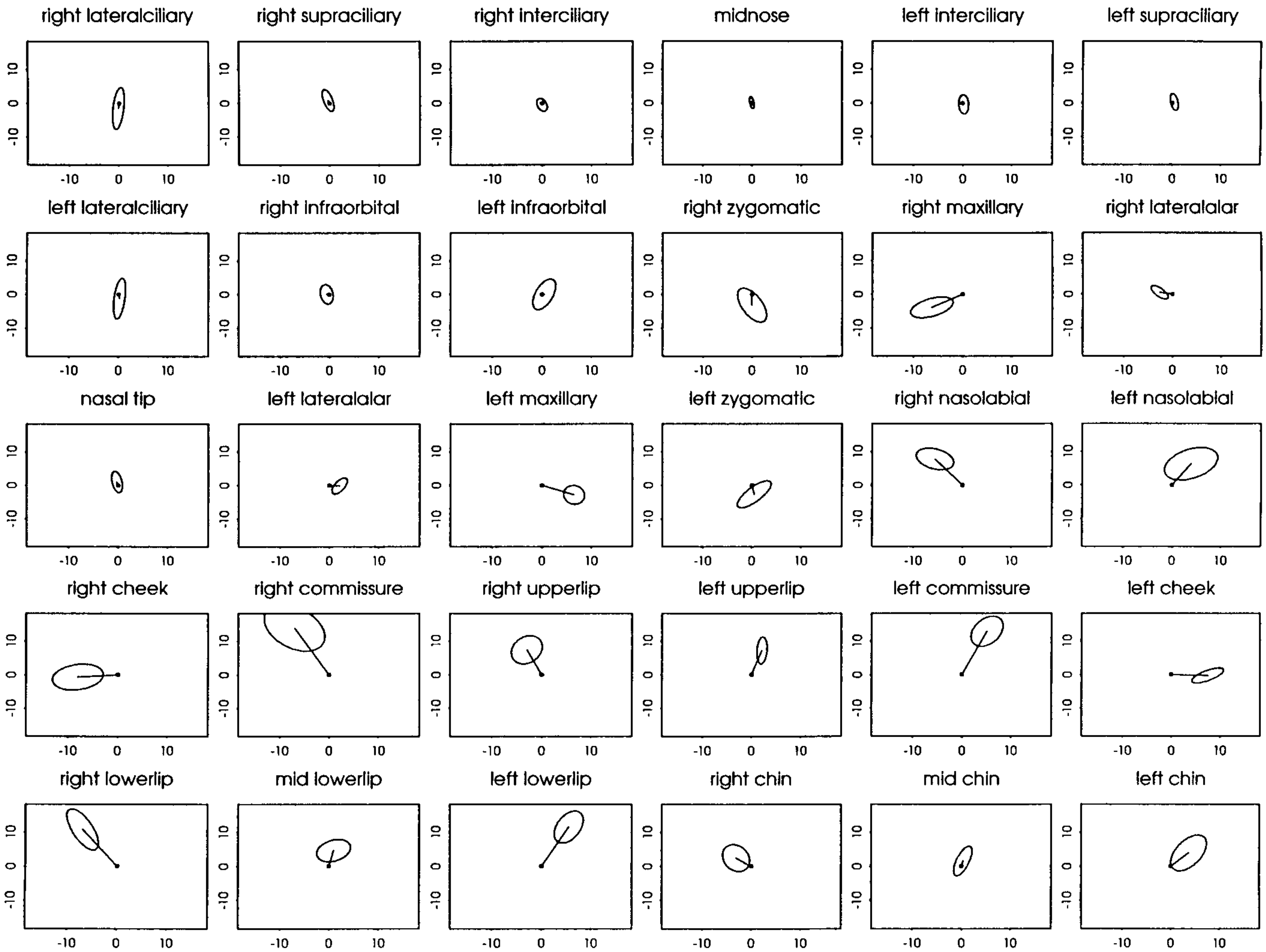

FIGURE 7 **Schematic representations of the horizontal two-dimensional vectors (with the subject facing the top of the page) for markers of the normal subjects during the smile animations (as in Figure 3). The greatest movements occur for landmarks on the mid- and lower face, and especially for those landmarks on the circumoral region.**

This measurement of marker displacement is not based on the usual Euclidean distance, because the displacements may occur in any direction around the envelope of variation (ellipse) for the vectors, and these directions must be accounted for. For example, observe the displacements from rest of two markers depicted in Figure 4E and 4F. Both markers have the same mean displacement, marked by the point "o" at the coordinate 5,5, and the same magnitude of variation; however, the marker in Figure 4F has a lower Mahalanobis score (0.50 or 50th percentile) than the one in Figure 4E (Mahalanobis score of 0.90 or 90th percentile). This difference in scores comes about because the marker in Figure 4F has a mean displacement that occurs along a direction of great variation, the long axis of the ellipse. The marker depicted in Figure 4E has the same mean displacement; however, it occurs along a direction of lesser variation; hence, it receives a higher score. In our study of displacement, we used the Mahalanobis percentiles to take into account the envelope of variation in scoring the movement of markers during each animation. For samples from a multivariate normal distribution in three dimensions, the Mahalanobis distance follows a chi-square distribution with three degrees of freedom. For more details, see Johnson and Wichern (1992).

In order to visualize the movement, the three-dimensional vectors were mapped in two dimensions on the frontal, sagittal, and horizontal planes of space. Figures 5 through 7 are schematic representations of these two-dimensional vectors for markers in the normal subjects during the smile animations.

Instrumentation Sensitivity to Functional Deficits

Mahalanobis scores for the circumoral markers of the six patients then were compared with those of the five normal subjects. These circumoral markers were among those with the highest Mahalanobis scores for the normal subjects during smiling and, therefore, the ones most likely to be sensitive to motor impairment. For each patient, the mean displacement vector was calculated for the three replicates of the smile animation. These mean displacements for each patient then were plotted on the distributions defined by the normal subjects.

TABLE 2 Percentile Scores for the Five Normal Subjects Generated from the Mean Initial Location to the Mean Maximum Displacement; Scores Approaching Unity Indicate Substantial Movement of the Landmark

		Animation					
Landmark	*Marker No.*	*Smile*	*Grimace*	*Lip Purse*	*Cheek Puff*	*Eye Opening*	*Eye Closure*
Right lateralciliary	1	0.080	0.994	0.533	0.179	1.000	1.000
Right supraciliary	2	0.211	0.998	0.369	0.014	1.000	1.000
Right interciliary	3	0.098	0.989	0.583	0.036	1.000	1.000
Midnose	4	0.011	0.999	0.906	0.290	1.000	0.815
Left interciliary	5	0.163	1.000	0.499	0.161	1.000	1.000
Left supraciliary	6	0.623	0.989	0.564	0.305	1.000	1.000
Left lateralciliary	7	0.158	0.999	0.877	0.138	1.000	1.000
Right infraorbital	8	0.999	0.996	0.740	0.126	0.550	1.000
Left infraorbital	9	0.995	0.992	0.407	0.141	0.460	0.989
Right zygomatic	10	1.000	1.000	0.862	0.605	0.953	0.999
Right maxillary	11	1.000	0.982	0.992	0.869	0.942	0.987
Right lateralalar	12	1.000	0.648	0.796	0.999	0.979	0.938
Nasaltip	13	0.486	0.208	1.000	1.000	1.000	0.222
Left lateralalar	14	1.000	1.000	0.998	1.000	0.855	1.000
Left maxillary	15	1.000	0.985	0.958	0.701	0.494	0.978
Left zygomatic	16	1.000	0.980	0.714	0.217	0.998	0.982
Right nasolabial	17	1.000	0.771	0.998	0.573	0.828	0.916
Left nasolabial	18	1.000	0.801	0.997	0.896	0.065	0.904
Right cheek	19	1.000	0.905	1.000	0.998	0.048	0.856
Right commissure	20	1.000	0.519	0.998	0.999	0.149	0.693
Right upper lip	21	1.000	0.652	0.824	0.985	0.001	0.352
Left upper lip	22	1.000	0.949	0.761	1.000	0.076	0.131
Left commissure	23	1.000	0.613	0.955	1.000	0.073	0.822
Left cheek	24	1.000	0.995	0.997	0.880	0.475	0.914
Right lower lip	25	1.000	0.064	0.865	0.866	0.002	0.426
Mid lower lip	26	1.000	0.044	0.377	0.783	0.042	0.323
Left lower lip	27	1.000	0.414	1.000	0.979	0.009	0.687
Right chin	28	0.961	0.624	0.870	0.278	0.005	0.466
Midchin	29	0.221	0.052	0.816	0.232	0.002	0.590
Left chin	30	0.945	0.317	0.693	0.122	0.397	0.732

Our instrumentation produced two measures of functional impairment: (1) The summed Mahalanobis distances for the five circumoral markers of each patient (or a ''total impairment'' score) and (2) the maximum Mahalanobis distance of the five circumoral markers of each patient (or a ''maximum impairment'' score). For the repeated ratings of the patients by our five panelists, we computed a mean patient ranking for each panelist and then an overall mean for each patient from the rankings of the panelists. The ranks of the patients based on the overall mean ratings then were compared with the ranks based on the instrument impairment scores.

Results

Table 2 gives the percentiles for the normal subjects. Figures 5 through 7 display the frontal, sagittal, and horizontal two-dimensional vectors of displacement, with the ellipses representing the 95th percentiles of displacement for markers during the smile animation of the five normal subjects. Figure 8 depicts the mean vectors of each patient plotted on the mean vectors and 95th percentiles of the five normal subjects in each of the three planes of space (frontal, sagittal, and horizontal) for the circumoral markers (20, 21, 22, 23, and 26). All the patients had Mahalanobis scores that lay outside the 95th percentile of the normal subjects. The comparison of the instrument rankings based on maximum Mahalanobis distances, and panel rankings were in almost total agreement (Table 3); there was disagreement only for the two most severely impaired patients (patients 3 and 5), with a reversal of their ranks (5 and 6 versus 6 and 5). When the instrument rankings were based on *mean* Mahalanobis distances, there was less agreement between the two methods; in addition to patients 3 and 5 having reversed ranks, so too, did patients 2 and 6.

Discussion

The first aim of this study was to determine which regions of the face show the greatest movement during specific mimetic movements. We found that a given animation is characterized by motions in specific regions of the face. For example, during the smile animation, landmarks on the mid- and lower facial regions (infraorbital, zygomatic, lateralalar, nasolabial, cheek, commissure, upperlip, lowerlip, and chin) demonstrated the greatest movement. A similar pattern of movement was seen during the cheek puff animation, except that the infraorbital and chin regions demonstrated minimal movement. For the grimace and eye closure animations, the upper and midfacial regions (lateralciliary, supraciliary, interciliary, midnose, infraorbital, zygomatic, maxillary, lateralalar, nasolabial, cheek, and upper-lip points) underwent the greatest movement. During eye opening, the upper and midfacial regions (lateralciliary, supraciliary, interciliary, midnose, zygomatic, maxillary, lateralalar, and nasolabial), excluding the upper lip and cheek, moved the most. Finally, during lip purse, almost all markers on the mid- and lower face (midnose, lateralciliary, infraorbital, zygomatic, maxillary, lateralalar, nasaltip, nasolabial, cheek, commissure, upperlip, and chin) demonstrated the most movement.

The circumoral markers demonstrated consistent, large movements during the smile animation, and were considered highly suitable markers against which to compare the functional impairment seen in the six patients (Table 2). The rankings of the smile animation for the patients and subjects (Table 3) demonstrate that the motion analysis instrument was sensitive enough to detect differences in movement among the patients and the control subjects. The six patients had functional problems of varying severity associated with the soft tissues of the circumoral region. For example, patients 3 and 5 had severe limitations in movement during smiling, as demonstrated by the Mahalanobis distances.

These limitations in movement were demonstrated clearly in Figure 8. Apart from movement of the lower lip in the frontal dimension, patient 3, with facial trauma had very little movement of the circumoral region, and patient 5 demonstrated movements in different directions than in the normal subjects. In contrast, patient 6 had little in the way of functional impairment. He had displacements that were very close to the envelope of variation of the normal subjects. Although characteristic patterns of movement were detected by our set of landmarks, it must be noted that our results were based on the

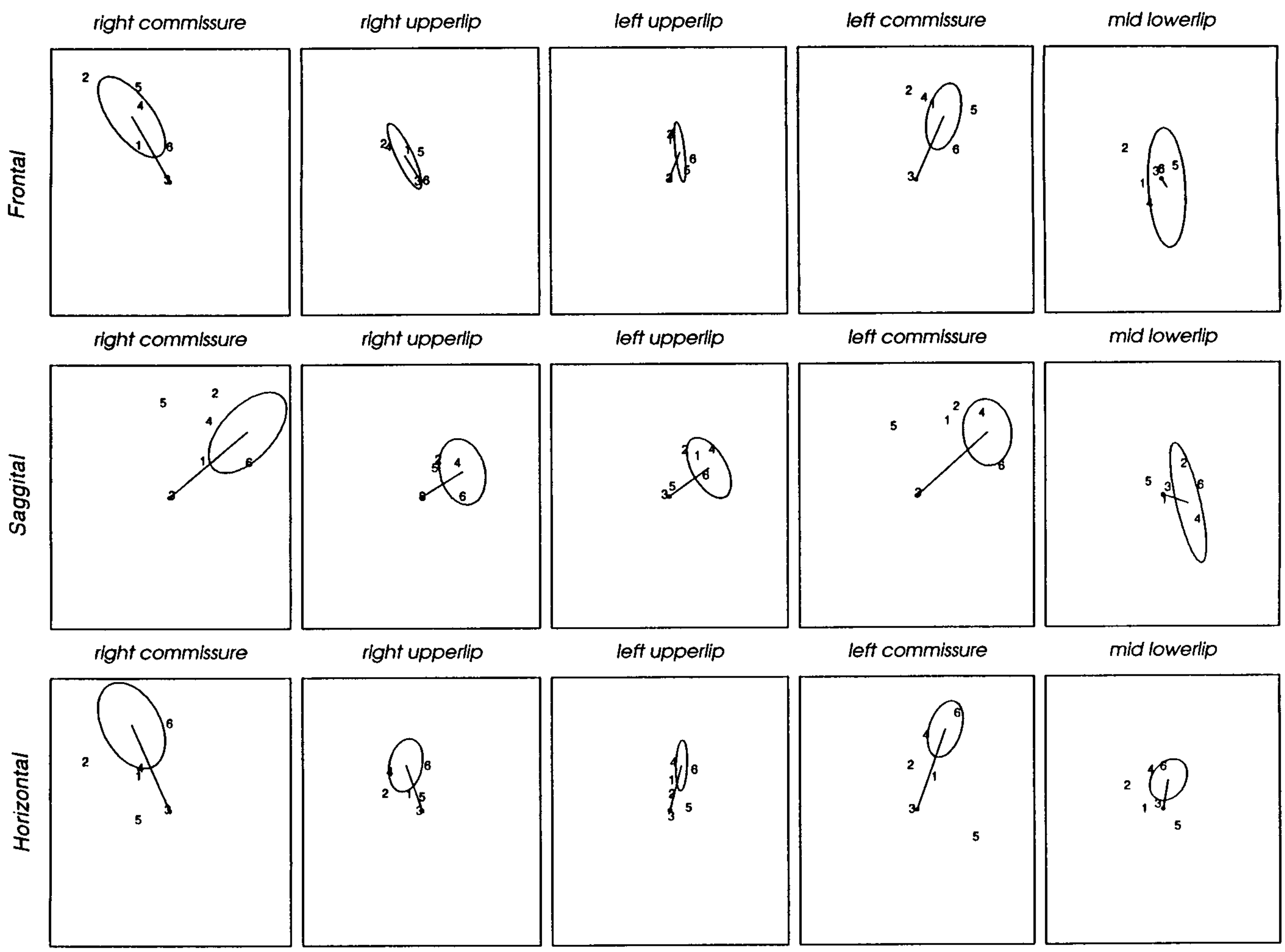

FIGURE 8 **Frontal, sagittal, and horizontal two-dimensional vectors (as in Figs. 3 through 5) and 95th percentiles of displacement for the circumoral markers (20, 21, 22, 23, and 26) during the smile animation of the five normal subjects and the six patients. Patient 1 has right facial paralysis; patient 2, a repaired bilateral cleft lip and palate; patient 3, facial trauma; patient 4, a repaired right unilateral cleft lip and palate; patient 5, a repaired bilateral cleft lip and palate; and patient 6, a repaired right unilateral cleft lip and palate. Patient 3, with facial trauma, had little movement of the circumoral region, and patient 5 had movements that were in different directions than those of the normal subjects. Conversely, patient 6 had the least severe functional problems and showed displacements that were close to the envelope of variation defined by the normal subjects.**

most mobile landmarks. Thus, an impairment in function of one facial region could result in compensatory movements of landmarks far removed from the site of impairment. This possibility implies that all landmarks should be analyzed in individuals with impaired function.

The rankings of impaired function of the patients by the raters were in close agreement with the instrument rankings;

TABLE 3 **Instrument and Panel Rankings***

	Instrument		
Patient	*Mean*	*Maximum*	*Panel*
1	2	2	2
2	3	4	4
3	5	5	6
4	1	1	1
5	6	6	5
6	4	3	3

* 1 = least severe; 6 = most severe.

however, there were differences based on whether the mean or maximum impairment scores (computed from the Mahalanobis distances) were used to calculate the final impairment score. It appeared that the panel members recognized a specific area of the circumoral region as having the most impairment, and this area correlated most closely with the marker that had the greatest (maximum) impairment score. The impairment score based on the mean of the circumoral markers thus reduces the ability of this instrument to detect impairment. An interesting dilemma for the raters was the difficulty in separating form and function during the ratings; one might expect that a patient with an obvious disfigurement will have a greater functional problem. In this study, however, we were able to demonstrate that, based on the most severely affected landmarks, the present method of analysis has the potential to provide a readily interpretable picture of the pattern of function so that the nature of both impairment and habilitation can be seen and, if necessary, measured.

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