Sensitivity of a Method for the Analysis of Facial Mobility. II. Interlandmark Separation

CARROLL-ANN TROTMAN, B.D.S., M.A., M.S.
JULIAN J. FARAWAY, PH.D.

Objective: **This study demonstrates a method of quantifying facial movements based on distortions of the skin surface.**

Design: **Landmarks were identified on the faces of five healthy human subjects (2 men and 3 women; mean age, 27.6 years; range, 26 to 29 years), and the distortions were characterized by changes in the separation between 20 pairs of landmark distances during specific maximal facial animations: smile, lip purse, cheek puff, grimace, eye closure, and eye opening. Data were recorded with a video-based tracking system for a period of 3 seconds at a sampling rate of 60 Hz or frames per second. For each subject, we analyzed the change in the separation of 20 pairs of landmarks, of which the majority were bilaterally symmetrical and functionally active.**

Results: **Characteristic patterns of movement emerged for each animation. We found that smiling involved movements of the lateral orbital, circumoral, and chin regions; grimacing involved the inner orbital, lateral orbital, lateral nasal, and upper-lip regions; eye closure involved the inner orbital, lateral orbital, and, to a lesser degree, lateral nasal regions; eye opening involved the inner and lateral orbital regions; cheek puffing involved the cheek and lower-lip regions; and the lip purse animation involved the nasolabial, cheek, commissure, and lip regions.**

Conclusion: **This measurement of distortion provided a quantitative estimate of facial movement, and this approach is especially applicable to patients with unilateral problems in which the patient can serve as his or her own control.**

KEY WORDS: *facial animation, functional data analysis*

Our studies of facial motion have a number of important dental applications (Trotman et al., 1996, 1998a, 1998b). In past reports, we described a video-based method of assessing facial motion by tracking the movement of retroreflective markers attached to defined facial landmarks. In this communication's companion paper (Trotman et al., 1998a), we examined the vectors of these landmarks during stereotyped animations and identified a number of landmarks that are sensitive to the repertoire of movement characteristic of each animation. While these animations were being recorded, the subjects were free to move their heads, thereby making it necessary to control for this movement. To this end, we used dental splints to carry markers that, because they were attached to the dentition, could be considered stable with respect to the head. To measure the movement of the soft-tissue landmarks on the head, the movement of the dental landmarks was subtracted from that of the various facial landmarks.

Because of the difficulty of measuring head movement in space, we have developed an alternative approach to the analysis of facial movement that requires no ''fixed'' landmarks. This alternative method sees facial movement as a ''surface'' distortion characterized by changes in the separation between any two landmarks on that surface, in this case the face. Based on our past work, patients with various forms of congenital and acquired facial disfigurements and functional impairment manifest deficiencies and distortions of facial motion that serve to alter the way the surface of the face is distorted. Measurements of landmark separation, therefore, should represent these deficiencies and distortions and thus should provide a quantitative estimate of facial movement. Although the change in separation between any two landmarks does not constitute an absolute measure of movement, it provides an overall index of mobility that can be used as an outcome measure for patients with facial impairment and thus serves to complement the analysis described in the companion paper (Trotman et al., 1998a). This approach is especially applicable to patients with unilateral problems where the patient can serve as his or her own control.

Dr. Trotman is Assistant Professor, Department of Orthodontics and Pediatric Dentistry, and Dr. Faraway is Associate Professor, Department of Statistics, University of Michigan, Ann Arbor, Michigan.

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Reprint requests: Dr. Carroll-Ann Trotman, Assistant Professor, Department of Orthodontics and Pediatric Dentistry, University of Michigan School of Dentistry, 1011 North University Avenue, Ann Arbor, MI 48109-1078. E-mail: ctrotman@umich.edu

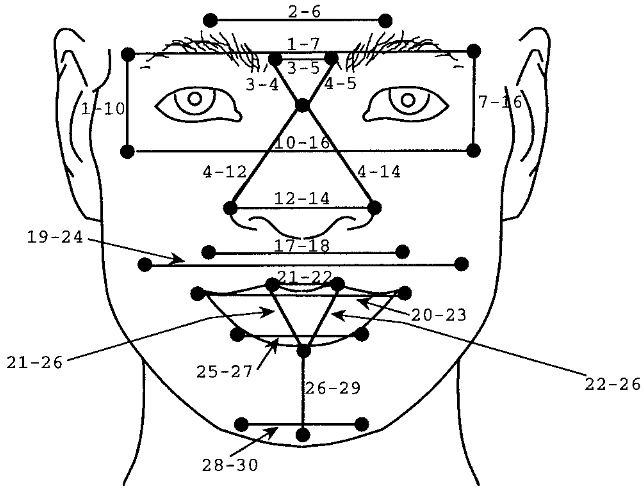

FIGURE 1 Interlandmark separation—the distance between selected landmarks. Lateralciliary width, point 1 and point 7; superciliary width, 2 and 6; medialciliary width, 3 and 5; right nasociliary, 3 and 4; left nasociliary, 4 and 5; right lateralorbit, 1 and 10; left lateralorbit, 7 and 16; zygomatic width, 10 and 16; right lateralnasal, 4 and 12; left lateralnasal, 4 and 14; alar width, 12 and 14; nasolabial width, 17 and 18; cheek width, 19 and 24; commissure width, 20 and 23; upper-lip width, 21 and 22; lower-lip width, 25 and 27; right interlabial, 21 and 26; left interlabial, 22 and 26; lip–chin, 26 and 29; and chin width, 28 and 30.

METHODS

The facial movements of five healthy human subjects (2 men and 3 women; mean age, 27.6 years; range, 26 to 29 years) were studied. An array of 30 retroreflective markers were secured to defined facial landmarks (Trotman et al., 1998a). The subjects were instructed to make six maximal facial animations from a relaxed initial position: smile, lip purse, cheek puff, grimace, eye closure, and eye opening. Each animation was repeated three times. Data were recorded with a video-based tracking system for a period of three seconds at a sampling rate of 60 frames per second. Given 30 facial landmarks, there are 435 possible interlandmark distances. For each subject, we analyzed the change in the separation of 20 pairs of landmarks (Figure 1). The majority of these separations were between bilaterally symmetrical, functionally active landmarks. These 20 pairs were chosen because their landmarks showed the most movement during the kinds of animations that we employed in this study and because of their intrinsic interest.

Data Analysis and Statistics

The three-dimensional change during an animation produces a characteristic change in the separation between landmarks (Bookstein, 1991). In all instances, these animations occurred in less than 3 seconds, so the data stream was truncated to include only the period of actual movement from the relaxed initial position. In addition, because the duration of each move-

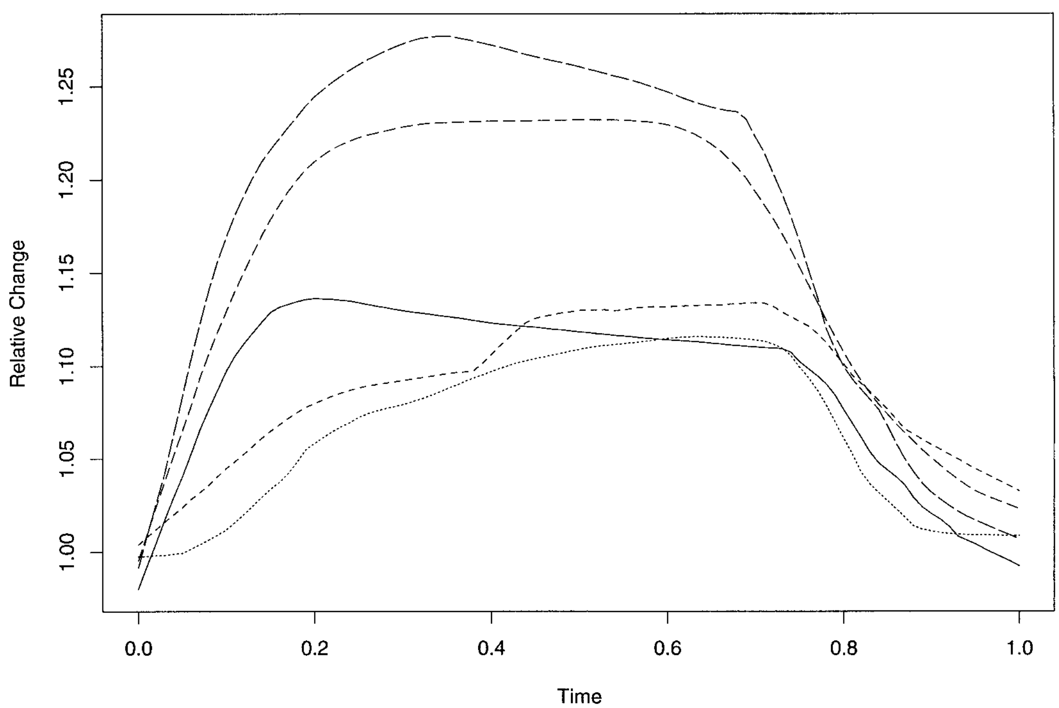

FIGURE 2 Plot of the average change in separation between landmarks on the right and left commissures (commissure distance) during the smile animation for the five subjects. The x-axis is the duration of the smile (scaled to unity). The y-axis is the relative change in the separation relative to the initial seperation: A value of one implies no change; a value greater than one implies an increase (for example, the value 1.24 implies a 24% increase), and a value less than one implies a decrease (for example, the value 0.9 implies a 10% decrease).

TABLE 1 Within- and Among-Subject Standard Deviations for the Percentage Change in Separation Between Pairs of Markers During Each Animation

	Standard Deviations	
Animation	*Within Subject (% change)*	*Among Subjects (% change)*
Smile	2.1	7.7
Grimace	1.3	9.4
Lip purse	2.1	7.2
Cheek puff	1.8	7.6
Eye closure	1.4	20.2
Eye opening	1.2	20.3

ment varied among animations, replications, and patients and because we wanted to compare the various animations, the data were scaled to a constant duration. To define the beginning and end of a movement, an algorithm was developed to detect a change in interlandmark separation; ‘‘rest’’ was defined as a period of no change.

Figure 2 is a plot of the change in landmark separation between the right and left commissures (commissure distance) during the smile animation. The x-axis represents the duration of the smile scaled to unity. The y-axis represents the change in separation relative to the resting distance. A value of one implies no change; a value greater than one implies an increase (for example, the value 1.24 implies a 24% increase), and a value less than one implies a decrease (for example, the value 0.9 implies a 10% decrease). The plot shows five curves, one curve per subject. Each of these curves is an average of the three replications of the smile animation of each subject. In order to obtain a measure of the change in separation between landmark pairs, the average of the five curves for each marker pair over the duration of the animation was calculated. Based on these averages, a ranking of the extent of the change in separation for each marker pair during an animation was produced.

To estimate intrasubject variability, standard deviations for the percentage change in separation of the landmarks on repeated animations (three replications per animation per subject) were calculated for each subject. For each animation, these standard deviations were averaged over the five subjects and the animation period.

To estimate intersubject variability, the mean percentage change in separation of the landmarks on repeated animations (three replications per animation per subject) were calculated for each subject. The mean and standard deviations of these means over all subjects then were calculated, and the standard deviations were used to compute the mean standard deviation over the animation period.

RESULTS

All numerical results in the tables are reported as percentage change. Table 1 summarizes the intra- and intersubject standard deviations for each animation for all pairs of markers. As would be expected, the within subject standard deviations were smaller than those calculated among subjects. The eye closure and eye opening animations demonstrated the highest intersubject variation. Table 2 summarizes the means, standard deviations, and rankings for the intermarker separation during each animation. Figures 3 through 8 are plots of the mean change in separation of the marker pairs (convert to percentage change by multiplying the values less than or greater than one by 100). From Table 2 and Figures 3 through 8, it can be seen

TABLE 2 Among-Subject Means, Standard Deviations (SD), and Rankings (Rank) of Percentage Change in Interlandmark Separations During Each Animation

		Animation											
		Smile		*Grimace*		*Lip Purse*		*Cheek Puff*		*Eye Closure*		*Eye Opening*	
Dimension	*Marker Pair*	*Mean*	*SD (Rank)*	*Mean*	*SD (Rank)*	*Mean*	*SD (Rank)*	*Mean*	*SD (Rank)*	*Mean*	*SD (Rank)*	*Mean*	*SD (Rank)*
Superciliary width	1-7	0.1	0.7 (20)	2.4	2.9 (16)	0.3	0.6 (20)	0.9	2.9 (17)	5.7	10.3 (7)	0.8	11.4 (12)
Lateral-ciliary width	2-6	0.3	0.7 (19)	7.3	10.3 (9)	1.1	2.6 (14)	3.0	12.7 (10)	14.0	33.4 (3)	1.0	29.5 (8)
Medial-ciliary width	3-5	1.4	2.9 (15)	5.7	16.4 (11)	1.8	4.1 (12)	3.9	14.6 (5)	5.9	15.2 (6)	2.2	15.5 (5)
Zygomatic width	10-16	0.03	2.5 (18)	3.6	3.8 (13)	0.5	0.7 (19)	0.7	1.4 (18)	6.0	11.0 (5)	0.7	11.9 (13)
Right lateral-orbit	1-10	14.8	8.8 (5)	12.7	11.6 (1)	1.3	4.7 (13)	0.1	7.0 (16)	16.4	55.5 (2)	10.8	55.7 (3)
Left lateral-orbit	7-16	14.5	9.4 (6)	10.9	12.3 (3)	1.0	4.6 (15)	3.0	11.0 (9)	16.9	46.5 (1)	5.8	45.3 (4)
Right nasociliary	3-4	1.0	4.4 (17)	4.9	5.2 (12)	1.8	5.1 (11)	3.0	6.0 (11)	1.0	65.2 (17)	30.2	61.0 (2)
Left nasociliary	4-5	1.2	1.8 (16)	11.2	9.9 (2)	0.8	4.0 (16)	1.5	12.4 (15)	11.1	84.9 (4)	31.4	82.9 (1)
Nasolabial width	17-18	9.1	10.2 (9)	6.1	13.6 (10)	7.0	7.1 (3)	3.3	5.8 (8)	4.4	7.2 (10)	0.6	10.6 (14)
Alar width	12-14	8.2	5.8 (11)	0.6	6.5 (20)	2.3	4.2 (10)	3.7	4.3 (6)	4.3	11.6 (11)	0.9	11.9 (11)
Right lateral-nasal	4-12	4.4	2.5 (12)	9.3	10.9 (5)	0.6	2.3 (18)	0.2	2.1 (20)	5.2	13.1 (9)	1.6	13.5 (7)
Left lateral-nasal	4-14	4.3	2.3 (13)	9.3	10.4 (6)	0.7	2.5 (17)	0.5	2.6 (19)	5.5	14.7 (8)	2.1	15.4 (6)
Cheek width	19-24	8.3	4.3 (10)	3.5	5.3 (14)	4.1	3.2 (5)	4.5	7.2 (4)	2.6	5.6 (13)	0.1	6.6 (19)
Commissure width	20-23	11.8	10.9 (7)	2.0	4.3 (18)	6.2	5.3 (4)	3.7	3.8 (7)	0.2	0.9 (20)	0.1	1.8 (17)
Upper-lip width	21-22	21.5	16.8 (1)	7.6	6.5 (8)	4.1	5.6 (6)	1.9	2.2 (13)	2.4	7.4 (14)	0.9	10.0 (10)
Lower-lip width	25-27	20.2	15.6 (2)	3.3	5.2 (15)	13.5	9.7 (2)	14.1	7.7 (2)	2.7	5.7 (12)	0.1	8.7 (18)
Right interlabial	21-26	15.1	18.0 (3)	9.5	21.0 (4)	3.6	15.8 (8)	1.8	10.3 (14)	0.5	3.4 (18)	0.4	3.1 (16)
Left interlabial	22-26	14.9	15.5 (4)	8.8	18.1 (7)	2.6	15.5 (9)	2.3	10.2 (12)	0.4	3.3 (19)	0.5	3.0 (15)
Chin width	28-30	11.4	7.0 (8)	1.5	3.9 (19)	3.8	6.3 (7)	6.8	8.5 (3)	1.7	3.7 (15)	0.1	4.6 (20)
Lip–chin	26-29	1.4	14.2 (14)	2.2	10.8 (17)	16.3	40.2 (1)	26.1	8.4 (1)	1.2	5.8 (16)	1.0	4.4 (9)

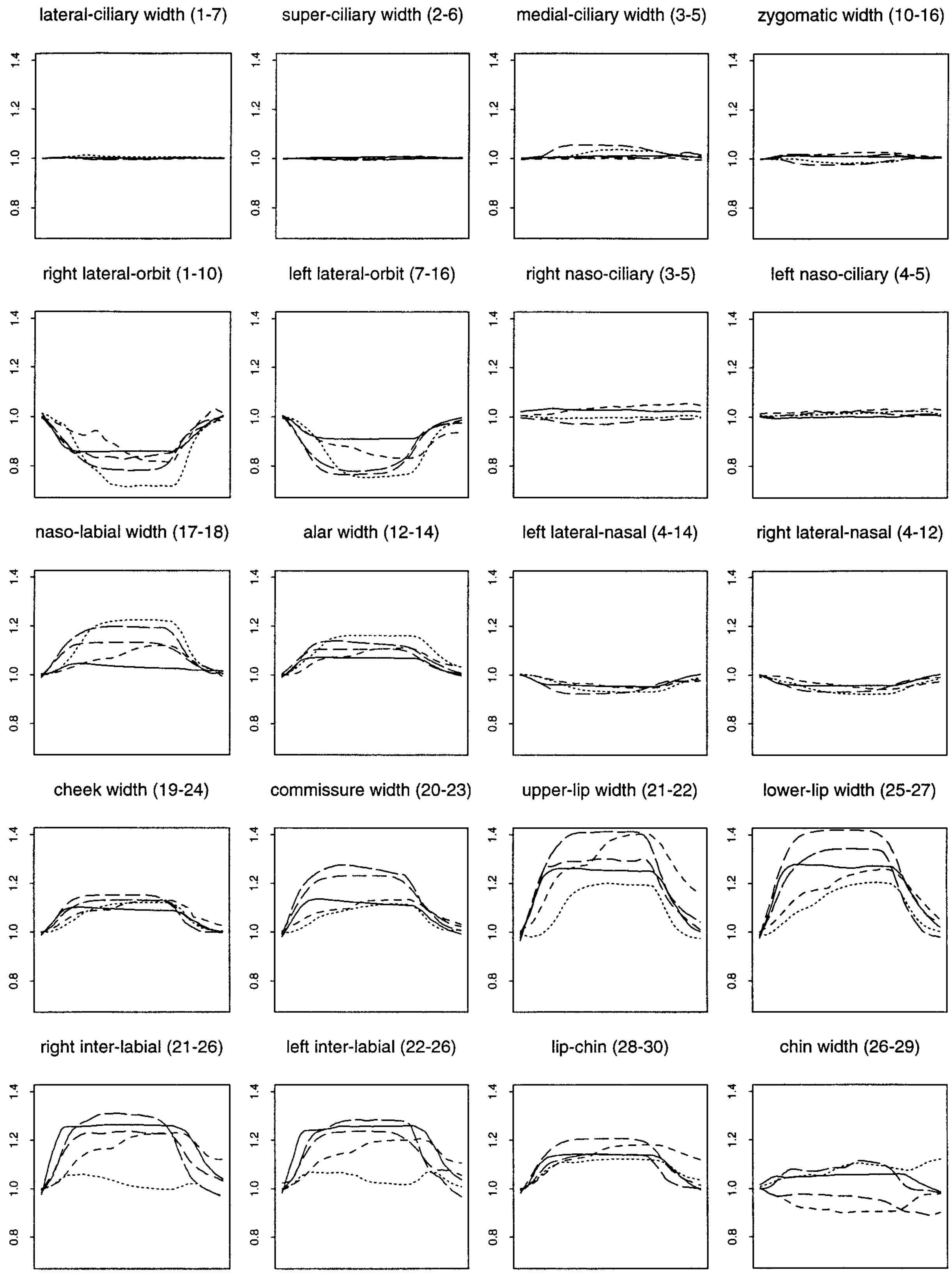

FIGURE 3 Change in separation (as in Fig. 2) between pairs of landmarks for the five subjects during smile animation. Smiling involves movements of the lateral orbital, circumoral, and chin regions.

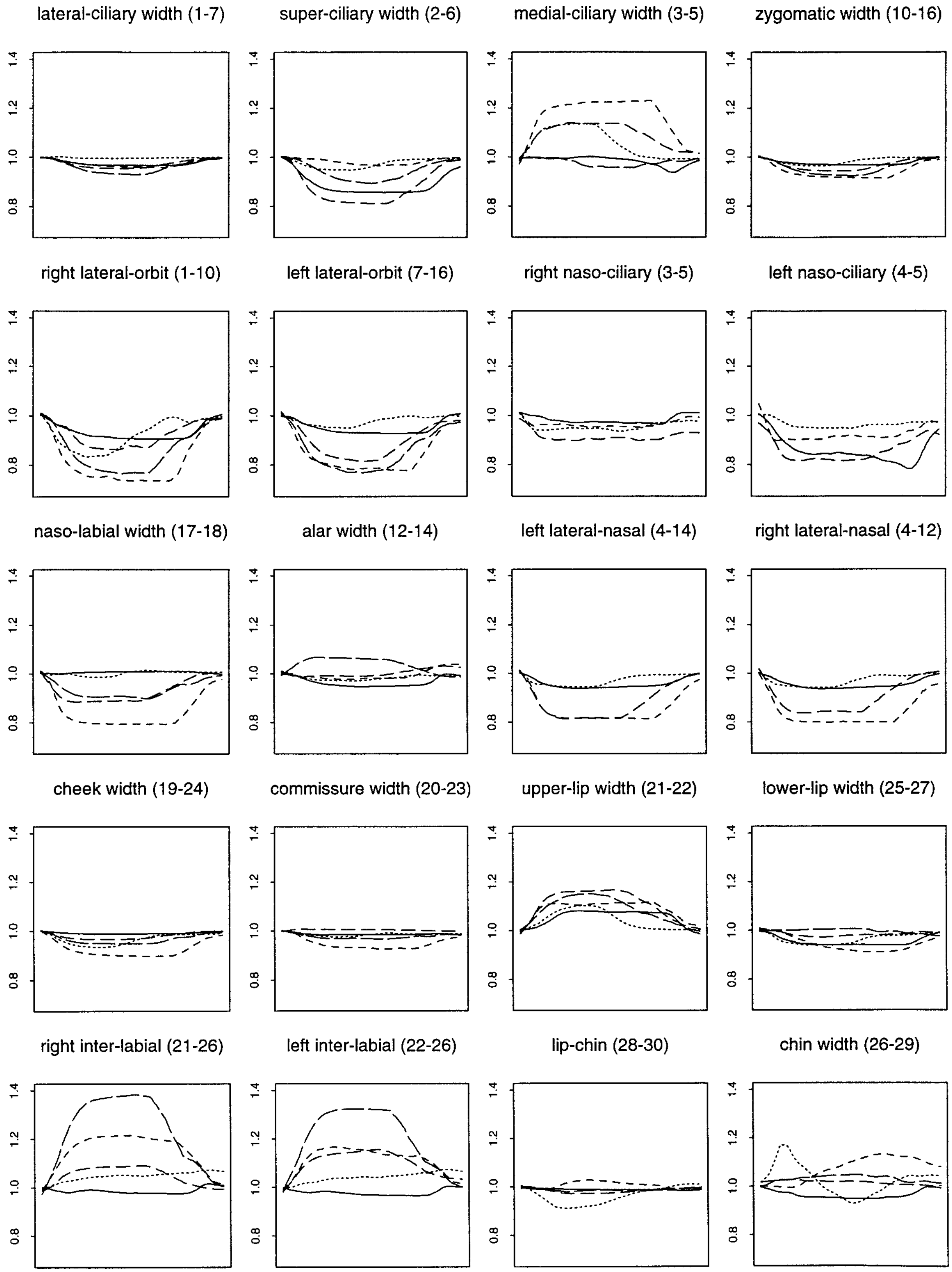

FIGURE 4 Change in separation (as in Fig. 2) between pairs of landmarks for the five subjects during grimace animation. Grimacing involves movements of the inner orbital, lateral orbital, lateral nasal, and upper-lip regions.

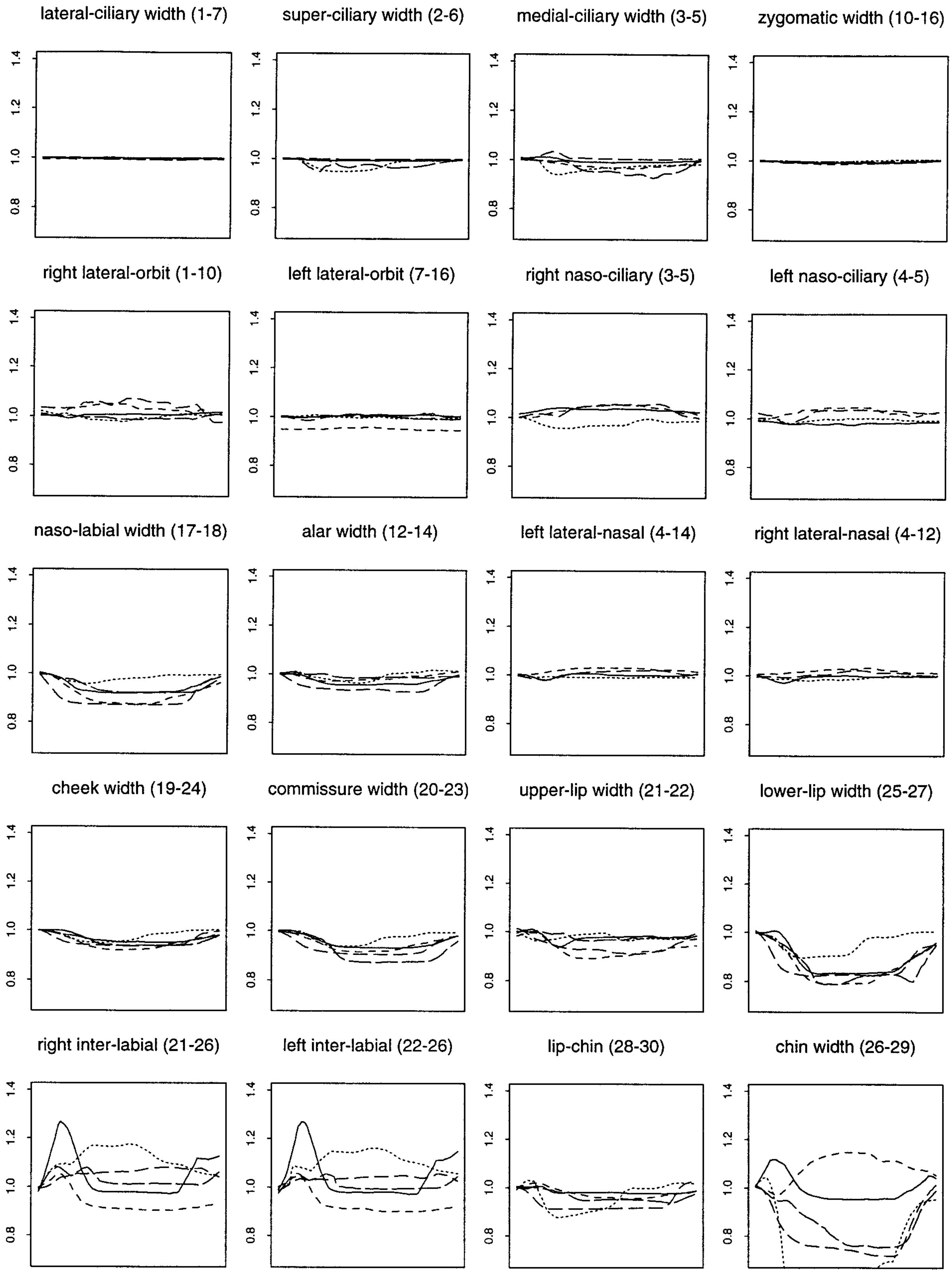

FIGURE 5 Change in separation (as in Fig. 2) between pairs of landmarks for the five subjects during lip purse animation. Lip purse involves movements of the nasolabial, cheek, commissure, and lip regions.

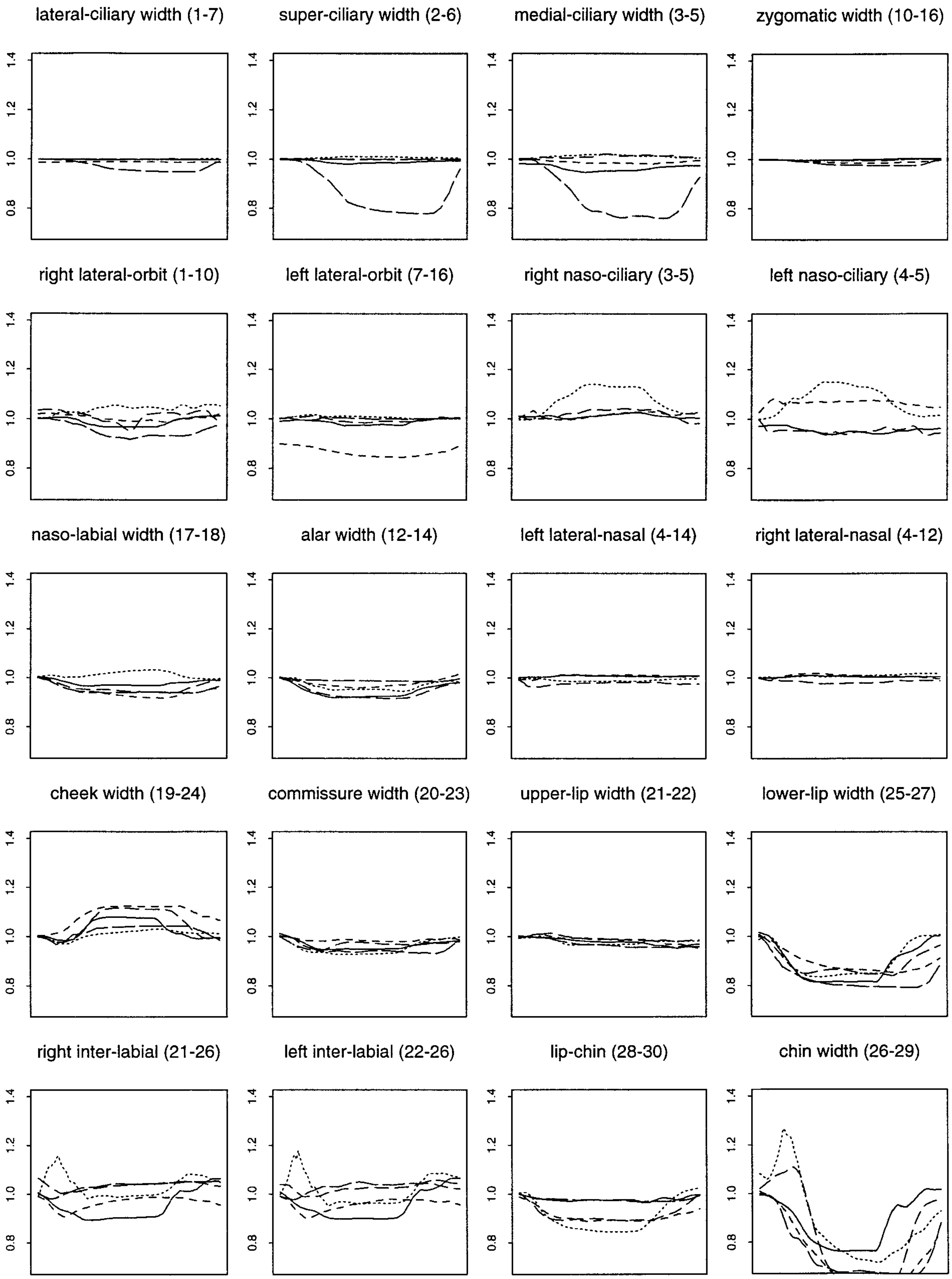

FIGURE 6 Change in separation (as in Fig. 2) between pairs of landmarks for the five subjects during cheek puff animation. Cheek puffing involves movements of the cheek and lower-lip regions.

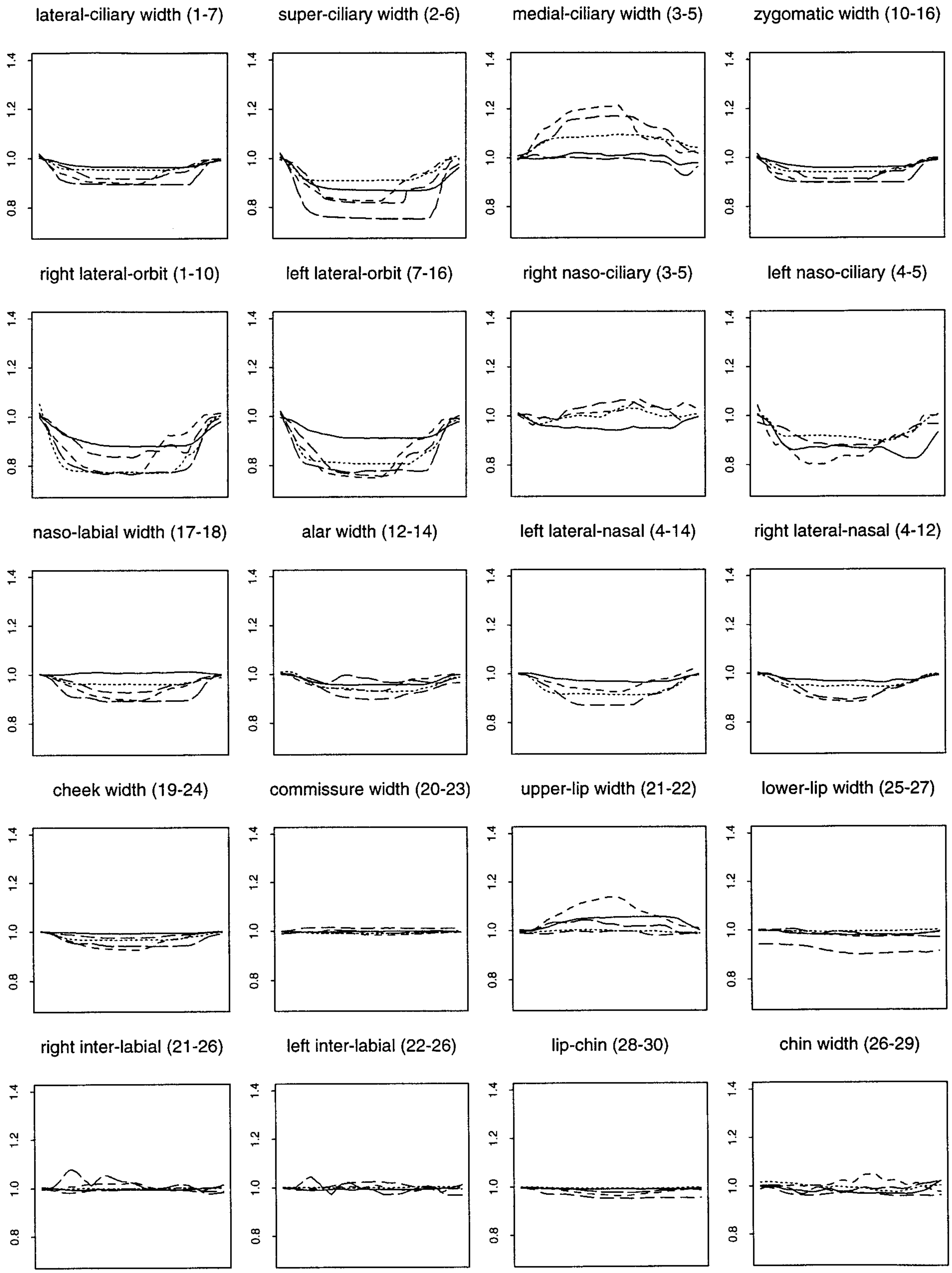

FIGURE 7 **Change in separation (as in Fig. 2) between pairs of landmarks for the five subjects during eye closure animation. Eye closure involves movements of the inner orbital, lateral orbital, and, to a lesser degree, lateral nasal regions.**

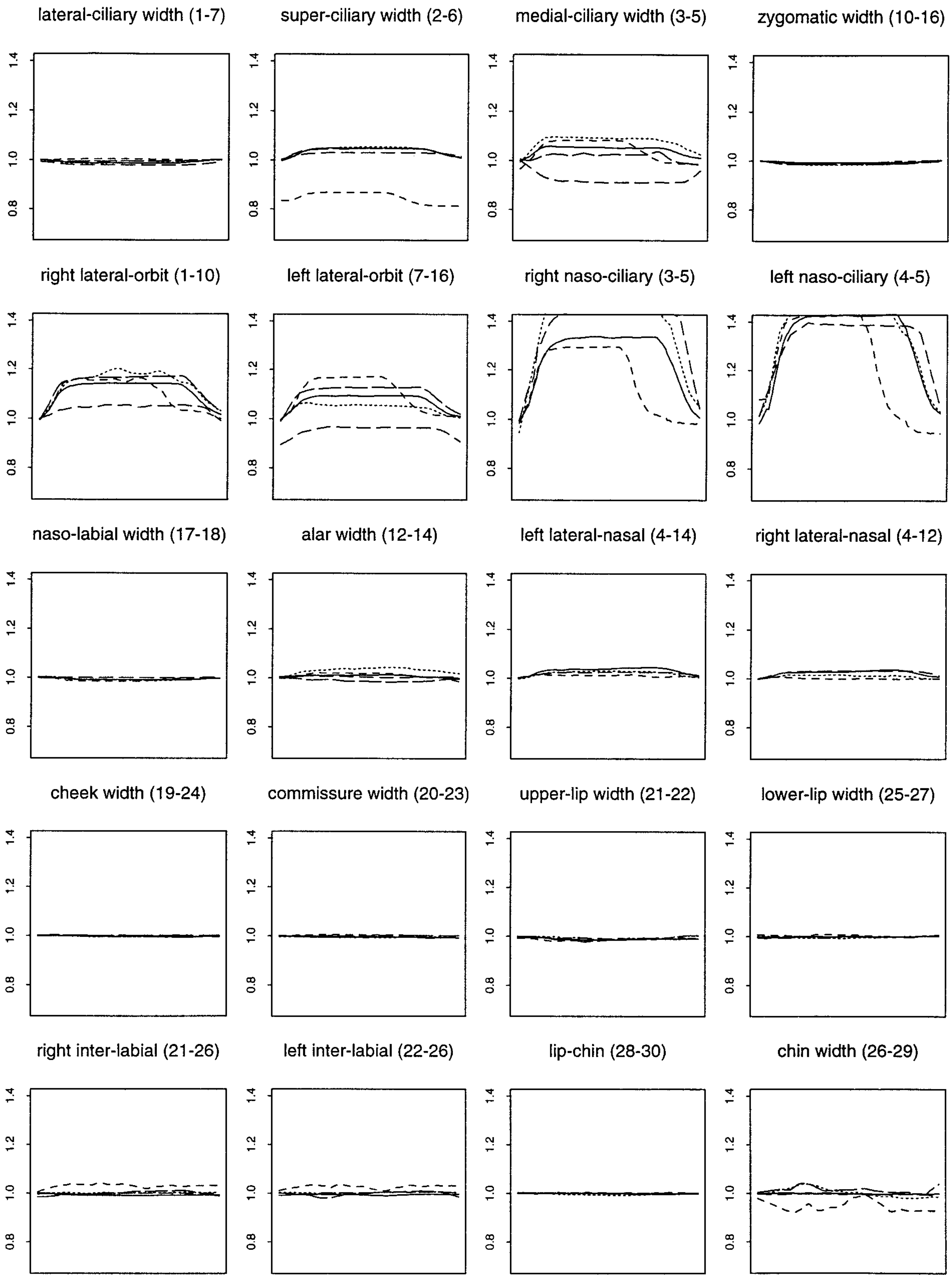

FIGURE 8 Change in separation (as in Fig. 2) between pairs of landmarks for the five subjects during eye opening animation. Eye opening involves movements of the inner and lateral orbital regions.

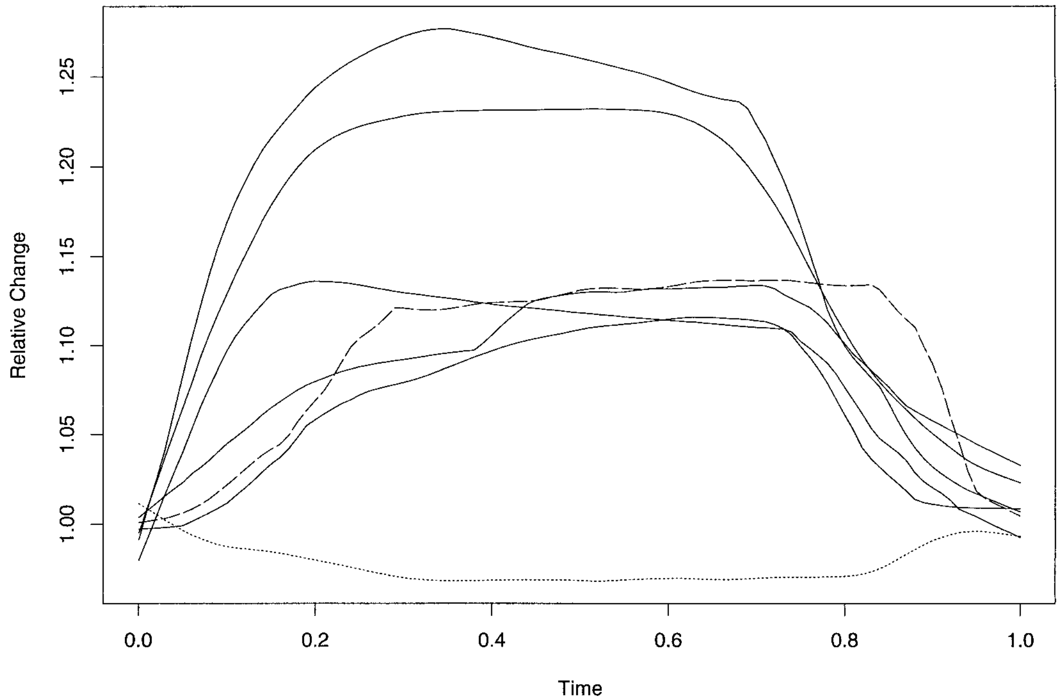

FIGURE 9 Relative changes in the commissure dimension of the five subjects and two patients during the smile animation. Patient 1, represented by the large dashed line, was an 11-year-old male with a repaired right unilateral cleft lip and palate. Patient 2, represented by the dotted line, was a 10-year-old female with severe scarring of the circumoral region following a traffic accident. Very little change in this dimension was demonstrated for patient 2 (x-axis scaled to unity).

that each animation produced consistent patterns of change in various regions of the face.

Discussion

From the present data, it may be seen that the change in separation of pairs of landmarks during specific animations produces a characteristic picture—a gestalt—that may be used to assess both the normal amplitude of motion among subjects and the within-subject changes that occur following various surgical reconstructive procedures or during the course of facial motor diseases. Because the subjects had no known facial motor problems, these variations in form represent an estimate of the normal range of activity. Smiling involved movements of the lateral orbital, circumoral, and chin regions; grimacing involved the inner orbital, lateral orbital, lateral nasal, and upper-lip regions; eye closure involved the inner orbital, lateral orbital, and, to a lesser degree, lateral nasal regions; eye opening involved the inner and lateral orbital regions; cheek puffing involved the cheek and lower-lip regions; and the lip purse animation involved the nasolabial, cheek, commissure, and lip regions.

Inspection of Figures 3 through 8 reveals that subjects often did not return to their original rest positions at the end of a motion; in most instances, they stopped somewhat short. This muscle hysteresis was evident throughout the recovery phase of movement for most landmarks. Also, we found that there is a wide range of "rest" positions (Figs. 3 through 8) from which a given animation may start or to which a given animation may return. As expected, variability among repeated facial movements was much greater within subjects than among subjects. Animations that involved maximal movements around the orbital regions (eye opening and eye closure) were most variable among subjects. For both maximum eye closure and eye opening, this increased variability was probably due to various other regions of the face being recruited to accomplish these movements. Additionally, the finding that there was a variable displacement of the lips relative to each other at the start and end of the lip purse and cheek puff animations was due to movement of the lower jaw during these animations.

Because it may be expected that subjects with larger faces will show greater displacements during a given facial movement, we adjusted for differences in facial size by measuring the percentage change in separation of landmarks from the relaxed position. However, confounding from differences of facial size probably was not controlled completely. Other potential confounders, such as age, gender, and facial shape, may exist. For example, Behrents (1985) demonstrated major changes in the soft-tissue morphology with age. Faces were larger; the skin was more wrinkled; the nose was bigger, with a downturned nasal tip; the nasolabial folds were more pronounced; and the skin thickness increased. Behrents also found size differences between males and females; females were generally smaller than males. These age changes and gender differences may affect facial movements; however, one important finding from this study was that the overall pattern of change in landmark separation was identifiable, quantifiable, and representative for each animation.

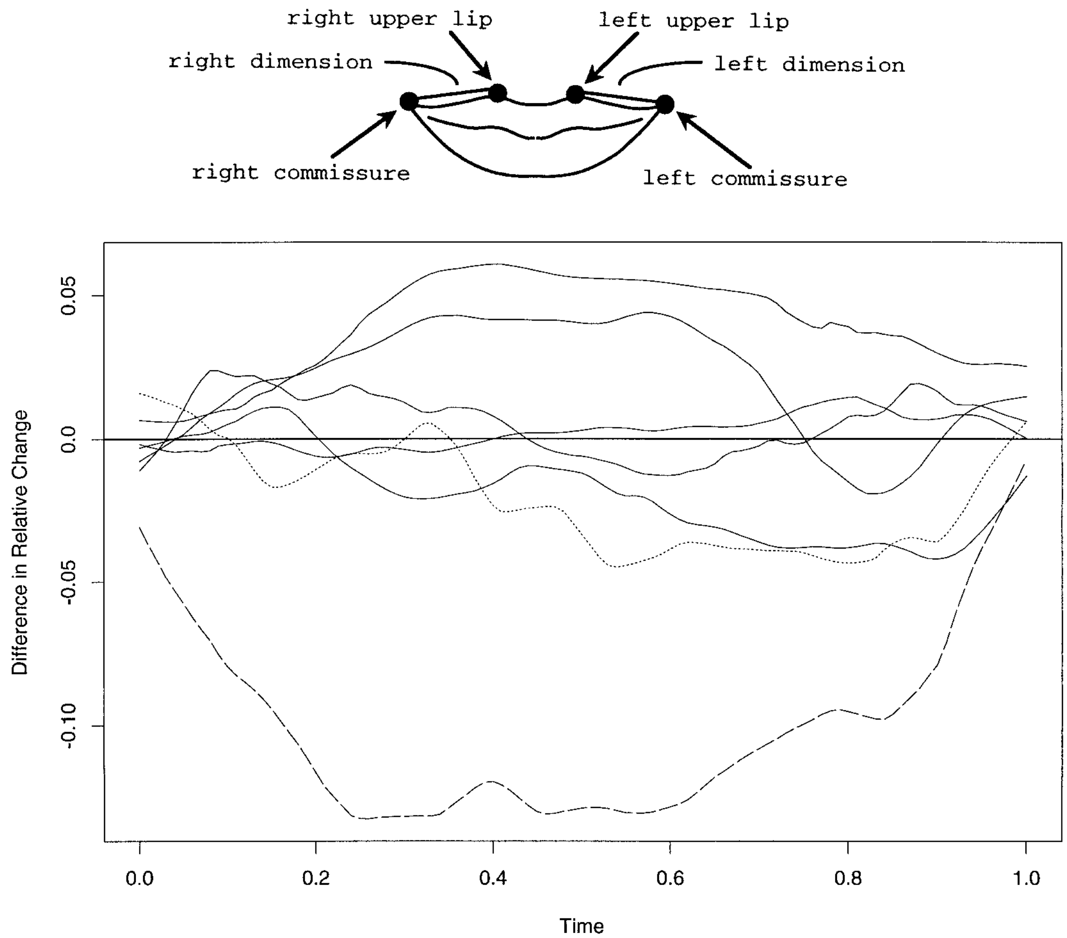

FIGURE 10 a: Symmetrical landmark pairs, one pair within the right side of the upper lip (the right commissure and right upper-lip point) and the other within the left side of the upper lip (the left commissure and left upper-lip point). b: Differences in separation between symmetrical landmark pairs depicted in a. The normal subjects show movement that is more or less evenly distributed about the zero line, implying symmetry of movement. Although the movement was small, patient 2, represented by the dotted line, also showed symmetrical movement. Patient 1, the unilateral-cleft patient, represented by the large dashed line, demonstrates a decrease in movement on the side with the repaired cleft (x-axis scaled to unity).

Our findings differ from those of recent studies on facial animation (Bush and Antonyshyn, 1996; Cacou et al., 1997; Johns et al., 1997). Two of these studies used two-dimensional measurements (Bajaj-Luthra et al., 1997; Johns et al., 1997), an approach that we consider unacceptable for the measurement of facial movements. The study by Cacou et al. (1997) used a laser surface scanner; a low-power laser beam was projected onto the face, and light reflected from the face was converted into three-dimensional facial images. Facial scans with the subject in a relaxed position and at ''the chosen facial posture or expression'' were recorded, and the differences in these two positions were analyzed for each expression. These results differ from those presented in this study in that the data were limited to two positions. We found that there is considerable information to be gained from an analysis of the entire movement during a particular animation.

To demonstrate the potential utility of our analytical approach, Figures 9 and 10 depict changes during the smile animations of two patients with different types of known functional impairment superimposed on the pattern of change seen in the five normal subjects. The first patient (represented by the large dashed line) was an 11-year-old male with a repaired right unilateral cleft lip and palate. The second patient (represented by the dotted line) was a 10-year-old female with severe scarring of the circumoral region following a traffic accident. Figure 9 displays the change from the initial position of the commissure distance during smiling. It can be seen that the patient with facial scarring (patient 2) demonstrated little or no change in this dimension compared to the five normal subjects; however, the cleft patient falls within the normal range. Figure 10b displays the difference in separation of two pairs of landmarks, one pair within the right side of the upper lip (the right commissure and upper-lip point) and the other within the left side of the upper lip (the left commissure and upper-lip point) as depicted in Figure 10a. The normal subjects showed movement that was more or less evenly distributed about the zero line, thereby implying symmetry of movement. Although the movement was small, the second patient also showed symmetrical movement. The unilateral cleft patient, however, demonstrated a decrease in movement on the side with the repaired cleft.

These changes in separation of landmark pairs were always measured relative to the rest position of the landmark pairs. Due to the relative nature of this measurement, therefore, the asymmetries that we detected with this analytical approach were associated only with function or movement. As discussed in the companion manuscript (Trotman et al., 1998a), an assessment of static asymmetries of facial form requires absolute, rather than relative, measurements. Both approaches to the analysis of facial movement, however, offer a complete description of facial movements. These analytical techniques and the methodology described can be used as an outcome measure for surgical reconstructive procedures in the habilitation of patients with functional deficits. The application of such an outcome measure is the focus of our present and future research.

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