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Automatic three-dimensional quantitative analysis for evaluation of facial movement☆

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Summary The aim of this study is to present a new 3D capture system of facial movements called FACIAL CLIMA. It is an automatic optical motion system that involves placing special reflecting dots on the subject's face and video recording with three infrared-light cameras the subject performing several face movements such as smile, mouth puckering, eye closure and forehead elevation. Images from the cameras are automatically processed with a software program that generates customised information such as 3D data on velocities and areas. The study has been performed in 20 healthy volunteers. The accuracy of the measurement process and the intrarater and interrater reliabilities have been evaluated. Comparison of a known distance and angle with those obtained by FACIAL CLIMA shows that this system is accurate to within 0.13 mm and 0.41°. In conclusion, the accuracy of the FACIAL CLIMA system for evaluation of facial movements is demonstrated and also the high intrarater and interrater reliability. It has advantages with respect to other systems that have been developed for evaluation of facial movements, such as short calibration time, short measuring time, easiness to use and it provides not only distances but also velocities and areas. Thus the FACIAL CLIMA system could be considered as an adequate tool to assess the outcome of facial paralysis reanimation surgery. Thus, patients with facial paralysis could be compared between surgical centres such that effectiveness of facial reanimation operations could be evaluated.

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Outcome studies are notably lacking in the evaluation of the diverse medical and surgical treatments for facial paresis and paralysis, or in the follow up of neurological disorders affecting the face. Moreover, to compare the effectiveness of different surgical techniques or even to compare the use of different free or pedicled muscle transplants for facial paralysis reanimation, it is necessary that there should be some consensus concerning the measurement systems. A major difficulty when comparing the reporting of these results is that each surgeon uses a different method to evaluate the surgical outcomes, making comparisons between surgical techniques very difficult.

Qualitative methods are available and are easy to apply, yielding various different intersubject and interobserver results. Several grading techniques have been developed for facial paralysis evaluation such as the House-Brackmann system, Sydney and the Sunnybrook Facial Grading System (SFGS).[1–4] However, these scales are subjective and ambiguous. The grades are arbitrary numbers in sequential order from least to most severe deficit, and the distance between each grade is not equal. They involve an assessment of the entire face, and are too broad to be useful for evaluation of a specific area of facial reconstruction. Furthermore, they do not provide information about dynamic facial movement.

To resolve this, several computerised systems have been developed to measure facial movement by analysing marked points on the face,[5–10] counting pixels,[11,12] looking at variation in light reflections,[13] or drawing contour lines of the surface[14] through photographs[8,11,15] or video recordings[5–7,9,10] of the patient's face. Although these methods mainly provide static information about different face landmarks at rest and when maximum movement is performed, and are time-consuming techniques, none of these methods provides complete information about 3D movement of facial vectors. In order to compare different surgical techniques or to follow up neurological disorders affecting the face, an objective measurement system should not only include static information, 3D dynamic information also needs to be determined. The goal of this study is to present an automatic, useful and practical tool for facial reanimation surgeons to assess accurately patients' facial movement.

Materials and methods

Subjects

Healthy subjects consisted of 20 females who ranged from 21 to 45 years of age (mean age 29; standard deviation [SD] 10). Inclusion criteria included clinically normal facial function and no history of facial paresis or paralysis, with no history of facial trauma or otologic surgery. Subjects were selected on a voluntary basis and were not compensated for their participation in the study.

Methods

The new objective measurement system that is proposed for evaluation of facial movement is called FACIAL CLIMA. It requires video recording and computer analysis of facial movements. The use of STT capture algorithms, which have been successfully applied in other settings,[16] is the key to the accuracy of FACIAL CLIMA's data. This language makes it possible to define points, angles, areas, vectors and velocities between facial plots.

Optical tracking system

The service provided by an optical tracking system is to deliver the 3D coordinates of the markers being tracked. Therefore, the output data coming from the tracking systems are the labels for the markers and their corresponding 3D coordinates. The process of providing these output data is known as tracking. In order to provide this information, the tracking system needs to be referred to a global reference frame. The process followed to define this reference frame is known as calibration.

Calibration

The calibration process allows the definition of a global reference frame for all the cameras used in the optical tracking system. The main goal of the calibration process is to compute the extrinsic and intrinsic parameters for each particular camera. The extrinsic parameters are those vectors and angles that define the position and orientation of each camera. The intrinsic parameters are numerical factors that define the particular characteristics of the optics used by each particular camera. The number and meaning of the intrinsic parameters depend on the mathematical model used for the lenses. The STT tracking system uses a non-linear mathematical model for the lenses, which takes into account the geometrical distortion generated by lenses of short focal length. For this particular case, the intrinsic parameters include the scale factors as well as the radial and tangential distortion coefficients.

In order to compute those parameters, the STT tracking system incorporates a software module that computes all those parameters in a fully automatic way. This computational module requires as input data a set of pictures of a calibration tool. This calibration tool includes a set of markers. The relative position between those markers is perfectly known. The projections of the markers in the calibration tool are computed on each frame taken in the calibration process. Using these data, the calibration module solves a set of non-linear equations where the input data are: the 2D projections of the markers in the calibration tool for each frame and the relative positions of the markers in the calibration tool. The solution of this set of non-linear equations provides the actual values of both the extrinsic and intrinsic parameters of the cameras.

Tracking

The main service provided by the optical tracking system is the computation of the 3D trajectories of a series of markers, which can be independent markers (particular points), markers located on a rigid body (flying object) or markers on objects linked together between them (like a human skeleton). Once the tracking system has been calibrated it can be used to perform the tracking as many times as needed.

The tracking process consists of two different processes that have to be run in a synchronised way. The first process takes the images from the cameras and extracts the 2D coordinates of the projections of the markers in the image sensors of the cameras. The second process takes these data and computes the 3D coordinates of the markers. These coordinates are computed using the extrinsic and intrinsic parameters of the cameras, which have been computed in the calibration process. The projection of a single marker on a particular camera provides information about the relative position of the marker with respect to the camera considered. The only information missing is the distance of the marker with respect to the camera. This unknown cannot be computed using the projection of that marker in a single camera. In order to compute this unknown information at least one more camera has to be used. The output of this step is a cloud of 3D points whose coordinates are known. The second problem tackled by the tracking service is the identification of the 3D coordinates corresponding to each marker existing in the tracked model. This step is called labelling. The input data for this step are the cloud of 3D coordinates while the output data are an ordered array of markers' names with their corresponding 3D coordinates. This information is passed through another module which will be in charge of computing the particular biomechanical magnitudes which are of interest for the particular analysis being performed.

Accuracy of measurement process used in the FACIAL CLIMA

In order to determine whether the video capture, computer software, and computerised analysis used in the FACIAL CLIMA process are accurate in measuring distance, velocity, angles and areas, a fixed distance of 90 mm and an angle of 90° were marked on a scaling rod with 2 mm wide reflective markers [3M(tm) Scotchlite (tm) reflective material − 8850 silver pressure sensitive adhesive film, St Paul, MN, USA] and videotaped. To minimise error, the scaling rod almost entirely filled the field of view. The observer manually moved in horizontal and in vertical position the segment within the area observed by the three cameras and the movement was captured by the computer.

For the measurements of distances and angles 42 captures of 1 s were taken, equivalent to 50 photograms per second. Captures are distributed as follows: 21 captures with the scaling rod in a vertical position and 21 captures with the scaling rod in a horizontal position.

The accuracy of the velocity measurements was assessed as follows. The distance between two markers is: d1,2 = sqrt((x1−x2)∧2 + (y1−y2)∧2 + (z1−z2)∧2). The velocity of shortening and lengthening of the vector formed by the two markers is the change of distances between the two markers divided by the time interval passed between the consecutive positions. Thus:

	Position1	Position2
M1	{x11,y11,z11}	{x12,y12,z12}
M2	{x21,y21,z21}	{x22,y22,z22}

Then, velocity is: distance in position 1: d12_1 = sqrt($(x11-x21)^2 + (y11-y21)^2 + (z11-z21)^2$); distance in position 2: d12_2 = sqrt($(x11-x21)^2 + (y11-y21)^2 + (z11-z21)^2$). Thus, velocity is: v12 = (d12_2−d12_1)/t. These data were automatically obtained by the FACIAL CLIMA system.

Intrarater and interrater reliability of the FACIAL CLIMA

For intrarater reliability, all markers were removed and then reapplied three times. Intraclass correlation was used to measure the re-test measurements. Intraclass correlation was also used to measure the agreement between raters. The question we are answering is whether the observers performing these measurements are interchangeable. The intraclass correlation is the correlation between one measurement (either a single rating or a mean of several ratings) on a facial landmark and another measurement obtained on that same landmark.

Data gathering

The calibration process is not required each time the acquisition of data is performed and takes just a few seconds to carry out. The capture process is very simple. First, the reflective markers have to be placed at several facial landmarks depending on the configuration chosen (Fig. 1). Facial markers did not impede movement of the face. The investigator previously defined these configurations. In our case, the facial inferior third landmarks were configured following the experience of Tomat and Manktelow.[15] On the other hand, we chose those landmarks at the upper third of the face that would most appropriately provide us with the quantity and velocity of two crucial movements in a patient with a facial palsy: eyelid closure and eyebrow elevation, following the experience of Frey et al.[17] A model definition script can easily configure both the number of markers and all the calculations to be carried out. The markers used for reference in the upper face (markers that do not move) are: 9, 10, 11, 12, 13 and for the lower face are: 1, 2, 3, 4, 7.

Once the reflective markers have been placed, the patient just has to sit in front of three cameras to ensure the capture of movement in 3D (B/N JAI M50 IR, 768 × 574 pixels, 50 images/s (Hz), JAI Inc., Copenhagen, Denmark) and the system automatically starts and processes the images (standard error resolution of cameras: 0.58 mm). The system uses three infrared foci for each camera (IR 850 nm, LED 60°, Derwent, Ireland), in order not to disturb the patient during the recording. The cameras and the infrared foci were mounted at a defined height and distance from the patient (1.2 m). To ensure that all markers are registered in 3D, the lateral cameras were rotated 30° converging on the central camera, while the central camera was 20 cm higher than the lateral cameras and rotated 15° downwards (Fig. 2). Because all facial points provide a reference from which the cameras are aligned, no device was used to fix the patient's head in place. The subjects were instructed to sit comfortably and remain as still as possible while fully performing the facial expression, and then to relax after each expression was performed. To record the upper face expression, subjects were instructed to close and open the eyes (not blinking) and to lift the eyebrows and relax. To record the lower face, subjects were

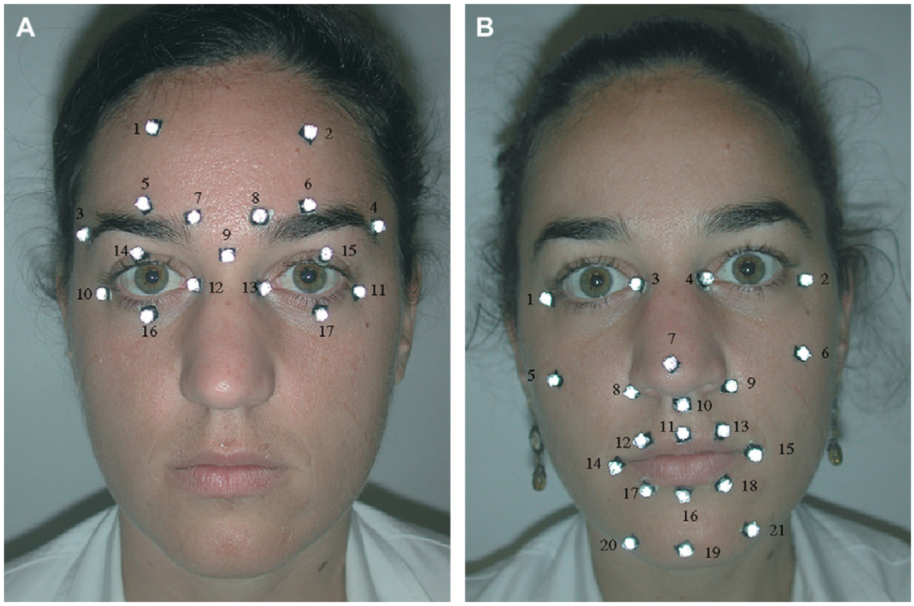

Figure 1 (A) The facial landmarks of the upper facial third: 1, right frontal; 2, left frontal; 3, right external eyebrow; 4, left external eyebrow; 5, right middle eyebrow; 6, left middle eyebrow; 7, right internal eyebrow; 8, left internal eyebrow; 9, nasium point; 10, right external canthus; 11, left external canthus; 12, right internal canthus; 13, left internal canthus; 14. right upper eyelid; 15, left upper eyelid; 16, right lower eyelid; 17, left lower eyelid. (B) The facial landmarks of the two lower facial thirds: 1, right external canthus; 2, left external canthus; 3, right internal canthus; 4, left internal canthus; 5, right zygomaticus; 6, left zygomaticus; 7, middle nasal point; 8, right nasogenian; 9, left nasogenian; 10, lower nasal point; 11, philtral point; 12, right mid upper lip; 13, left mid upper lip; 14, right commissure; 15, left commissure; 16, lower lip midpoint; 17, right mid lower lip; 18, left mid lower lip; 19, mid chin point; 20, right chin; 21, left chin.

instructed to smile with the mouth closed, with their lips together, and then allowing the lips to return to a resting state. They were then asked to perform upper lip elevation and relax, show the lower teeth and relax, and finally pucker their mouth and relax. Two sets of movement are required from the volunteers. The software directly prorates the maximum and minimum results of movement.

The capture process may last from a few seconds to up to one minute. However, 12 s are enough time to record upper face movement and 16 s for the lower face expression. The images were captured with the patient facing the central camera directly. The video image was transferred to a standard computer and edited using FACIAL CLIMA (V 5.2, 2005, STT Inc., San Sebastian, Spain) with a special frame recorder (Meteor II multichannel, Matrox Inc., Montreal, Canada). This system has also been used to analyse the angular position, range of motion and velocity of arm elevation.[16]

After this short period of time, all the biomechanical information about facial motion is available. Segments between facial markers are automatically drawn by the computer, with a green line indicating correct gathering of data (Figs. 3 and 4).

If error is present during the acquisition of data then a red line automatically links the reflective dots. The

Figure 2 Position of cameras. To assure that all markers are registered in 3D, the lateral cameras were rotated 30° converging on the central camera, while the central camera was 20 cm higher than the lateral cameras and rotated 15° downwards.

software includes a database for patient data storage, 3D views, biomechanical graphs, video images of the patient, and a report module that generates automatic reports in Microsoft Word. For each marker configuration and for any kind of movement, FACIAL CLIMA provides basic statistical data concerning parameters. Two-dimensional graphics are also available when the subjects are visualised on the screen (Fig. 5). The records are stored on the PC and can be accessed at any time. Finally, patients not only have a list of captured files, but also some other data, such as pictures, or data from electromyography, RMI or CT can be stored.

The parameters studied on both sides of the face were: amplitude of frontal angle, shortening of frontal vector, velocity of eyebrow elevation, area of frontal triangle, amplitude of palpebral angle, shortening of palpebral vector, velocity of eye closure, amplitude of nasolabial angle, shortening of zygomatic vector, velocity of shortening of zygomatic vector, amplitude of cheek area, and finally, smile angle (Fig. 6).

Results

Accuracy of measurement process used in the FACIAL CLIMA

Assuming the callipers represent the 'exact' measurement, the deviation (standard error) of the FACIAL CLIMA measurement from the calliper measurement was 0.11 mm in the horizontal position and 0.14 mm in the vertical position (mean 0.13 mm). Thus, in relation to the distances measured, the FACIAL CLIMA results varied from the calliper results an

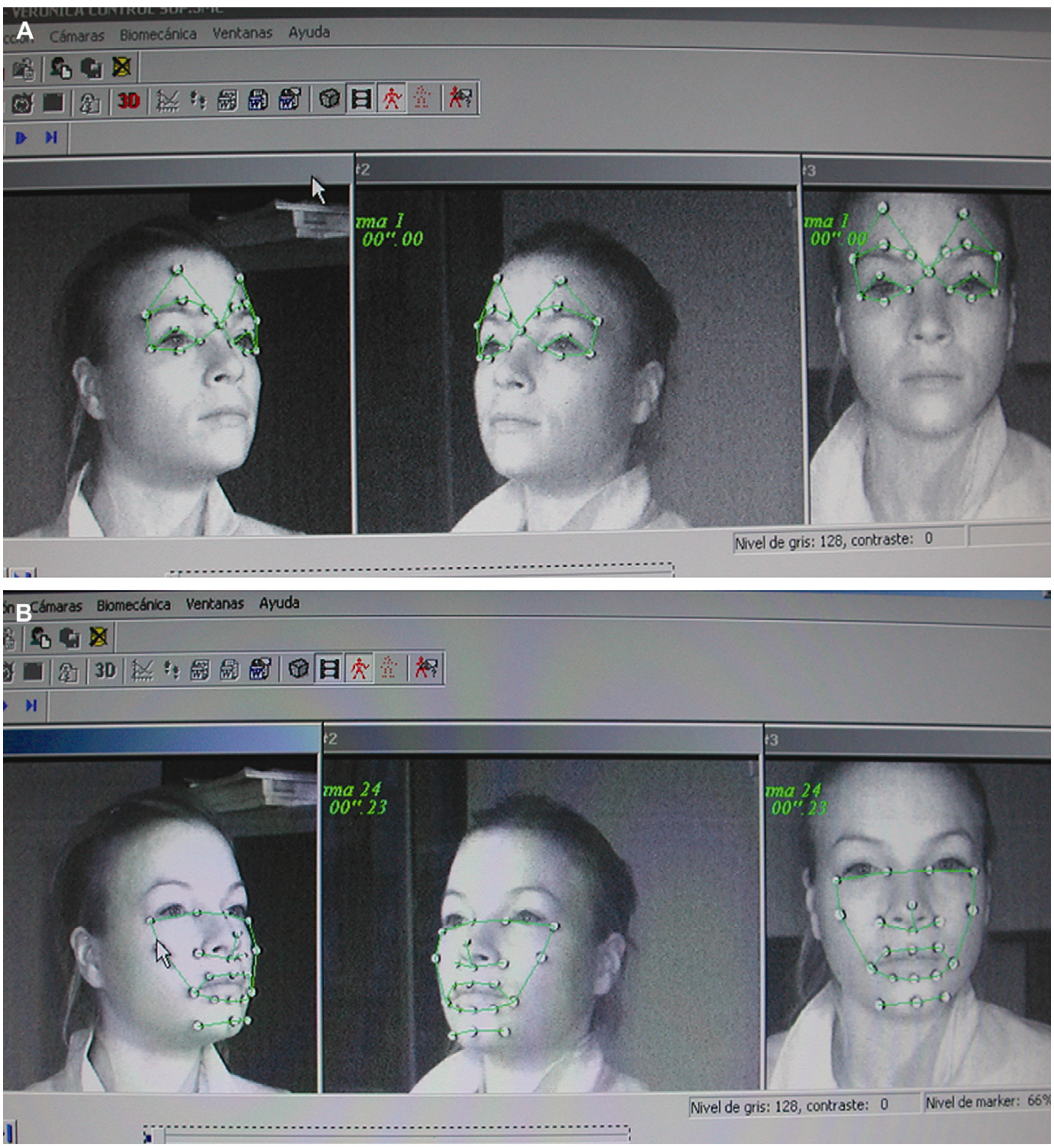

Figure 3 This figure shows three pictures of a face covered by the three cameras showing all upper facial plots (A) and lower facial plots (B).

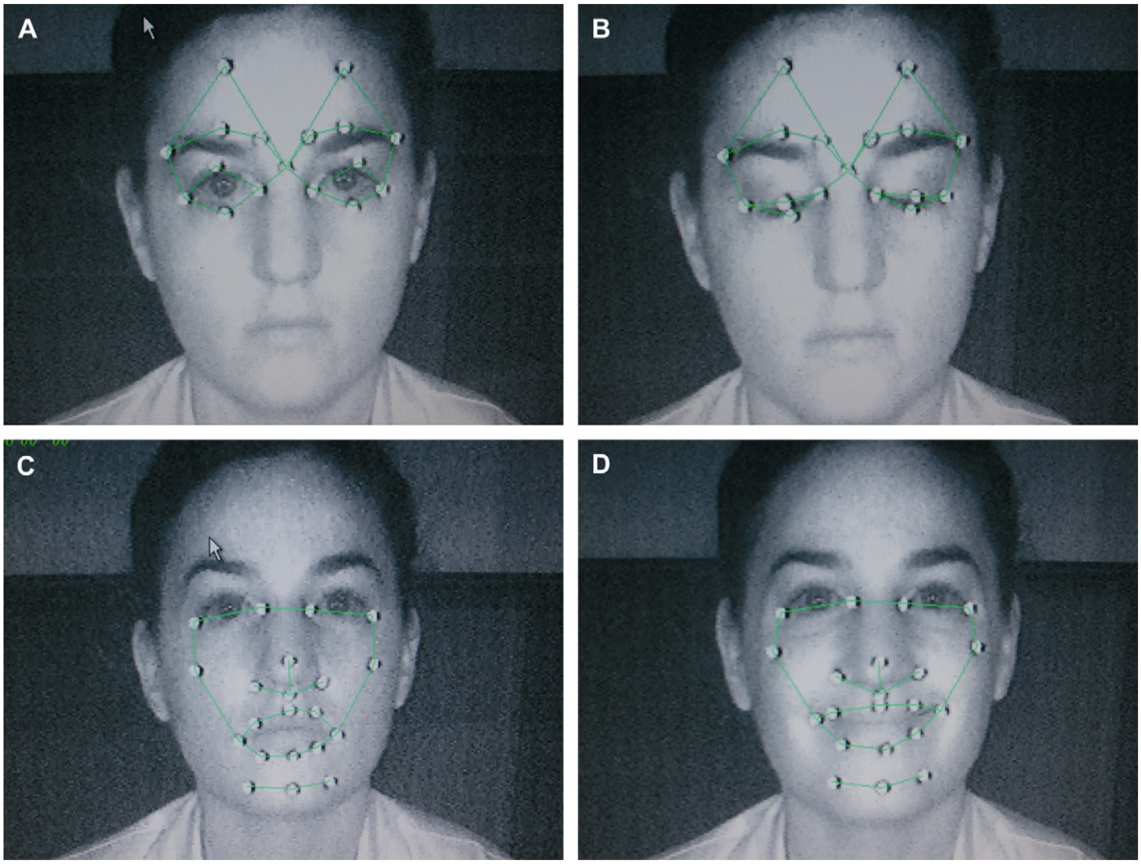

Figure 4 The system automatically links the facial plots to form green lines indicating that the capture process is correct. The segments move during the facial expression of the patients. (A) and (B) show the upper facial record in resting position and closing the eyelids, respectively. (C) and (D) show the lower facial record in resting position and smiling, respectively.

average of 0.11%. Similarly, assuming the calliper measurements represent the 'true' angle, the FACIAL CLIMA angle deviated from the mean true angle 0.39° in the horizontal position and 0.42° in the vertical position (mean 0.41°). Thus, in relation to the angles measured, the FACIAL CLIMA results varied from the calliper results an average 0.41%.

In Tables 1—4 the numerical data of the measurements performed are shown. Table 1 shows the measurements of the distance calculated in horizontal position, mean standard deviation and the percentage difference of the mean value of the calculated distance with respect to the nominal value. Table 2 shows the same parameters as before for the total measurements in the vertical position. Tables 3 and 4 show the measurements of the angles calculated in each position, mean standard deviation and the percentage difference of the mean value of the calculated angle with respect to the nominal value. Table 2 shows the same parameters as before for the total measurements.

Intrarater and interrater reliability of the FACIAL CLIMA

The intrarater reliability (re-test reliability) of the distance measurements for the facial reanimation measurement system technique was highly accurate, with an intraclass correlation of greater than 0.9 for facial parameters shown in Table 5 (see Fig. 6), for both raters. The average intrarater reliability for distances measured was 0.94 and 0.95 for raters 1 and 2, respectively. The interrater reliability (agreement between raters) of the distance measurements for the FACIAL CLIMA was highly accurate, with an intraclass correlation of greater than 0.9 for facial parameters shown in Table 6 (see Fig. 6). The average intraclass correlation for all facial parameters was 0.92. The mean time for calibration of the system was 4 ± 0.3 s.

Discussion

In order to evaluate the effectiveness of facial paralysis reconstruction, to detect changes over time after surgery, or to evaluate treatment of neurological disorders affecting face movement, it is necessary to use a quantitative measurement system that will evaluate not only facial position but also 3D movement, and give an exact determination of facial expression. Using quantitative methods to analyse face movement, the physician can evaluate a patient's progress before or after surgery and compare the effectiveness of different operative or medical procedures.

House summarised eight subjective classification systems of both historic importance and current use, classifying them as gross scales.[18] House-Brackmann later described their system, which was the widely accepted

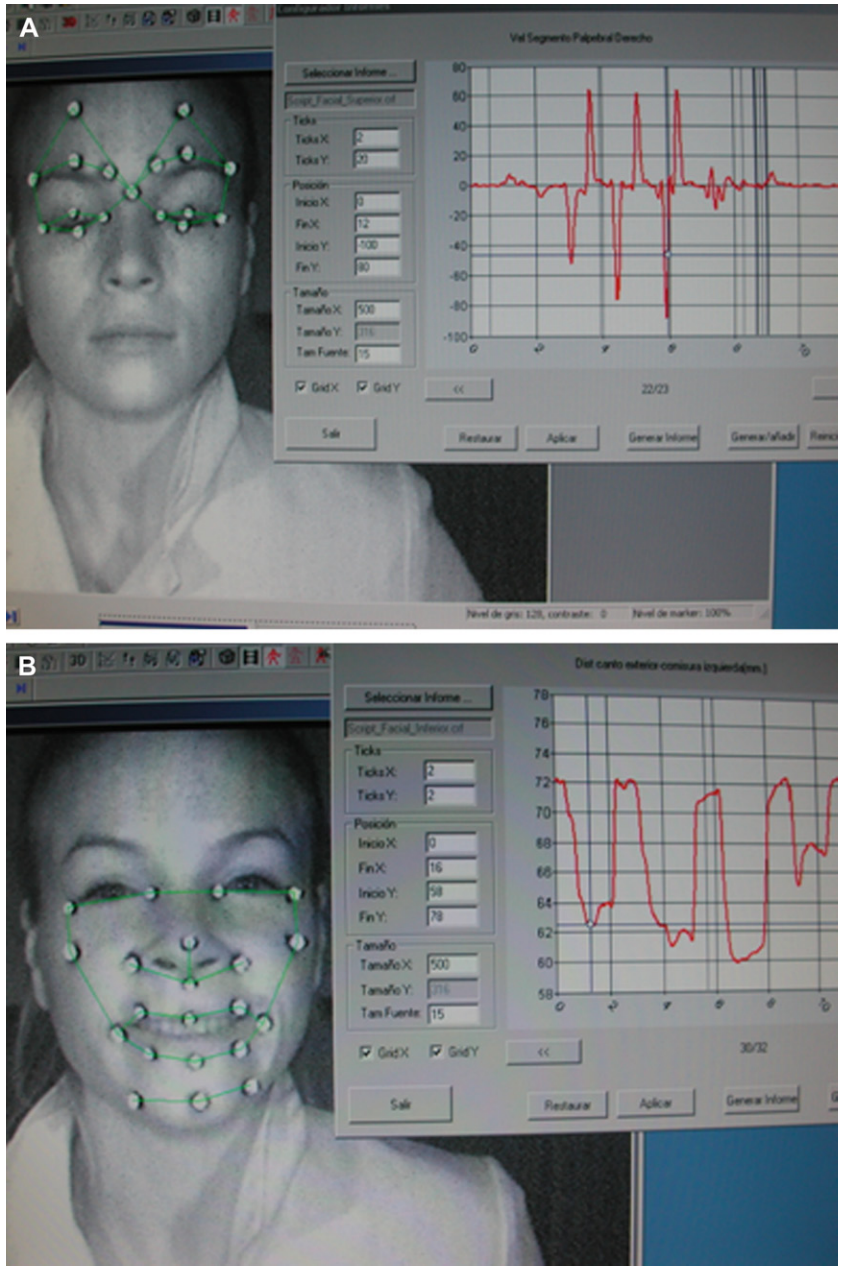

Figure 5 The output includes a graphic display of the movement of points on any two axes and the movement of points over time of the upper (A) and lower (B) facial movements.

system used to describe the grade of a facial paralysis.[2] However, this system requires the observer to give one grade that presumably evaluates the degree of paralysis and the secondary defects at the same time. The grades are arbitrary numbers in sequential order from least to most severe deficit and the distance between each grade is not equal. Because these grades are arbitrary, they cannot be mathematically manipulated. A major problem with this model and other subjective models is the large interobserver disagreement,[5,19,20] and the fact that this method is insensitive to small movements of the face, yielding a paucity of data to fully describe facial movement. In order to answer the common criticism of the House-Brackmann facial grading system, Ross et al.[3] developed a sensitive, clinical facial assessment of facial function. However, the range of scoring does not reflect clinically important changes and this system is also vulnerable to observer disagreement and bias. The Sunnybrook Facial Grading System is a system that scores the facial movement from 0 to 3 also evaluating facial sinkinesis. Although, it has shown a very good reported reliability and a high interrater agreement, this method also provides qualitative information.[4]

One way to quantitatively measure facial movement is to detect surface changes during facial expression.[12,21] Meier-Gallati et al.[13] and Scriba et al.[22] presented their experience with the Objective Scaling of Facial Nerve Function Based on Area Analysis (OSCAR) using variations of luminance produced by changes in facial expression. With the

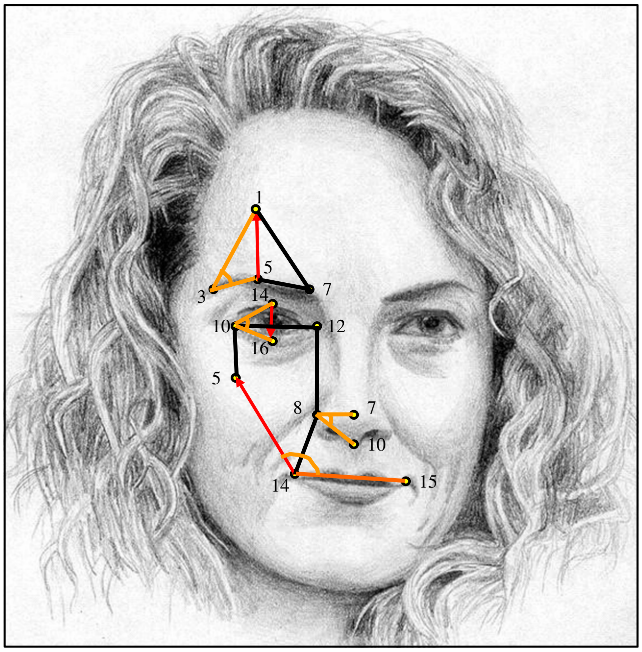

Figure 6 Main facial plots used for determination of length, angles, and velocity of segment shortening and surface between landmarks. The frontal, nasolabial and smile angles are displayed. Frontal segment between 1,5; palpebral segment between 14, 16; zygomatic segment between 5, 14. Frontal area among plots 1, 3, 5, 7; cheek area among 10, 12, 5, 8, 14. Frontal angle among 1, 3, 5; palpebral angle among 10, 14, 16; nasolabial angle among 7, 8, 10 and smile angle among 5, 14, 15.

Table 1 Precision analysis of distances in horizontal position

Position	Mean	Deviation	%
1	90.029	0.3282	0.0327%
2	89.17	0.1654	0.0926%
3	89.977	0.2819	0.0254%
4	90.099	0.1493	0.1102%
5	90.144	0.1435	0.1599%
6	90.074	0.1975	0.0828%
7	90.182	0.3544	0.2023%
8	90.128	0.1746	0.1418%
9	90.181	0.2940	0.2014%
10	90.114	0.2224	0.1271%
11	90.137	0.2662	0.1525%
12	90.247	0.2109	0.2739%
13	90.094	0.2175	0.1041%
14	89.991	0.3812	0.0100%
15	89.776	0.5287	0.2492%
16	90.245	0.6223	0.2724%
17	90.108	0.7799	0.1198%
18	90.074	0.5141	0.0827%
19	90.038	0.1745	0.0421%
20	89.985	0.1735	0.0164%
21	90.109	0.1506	0.1212%
Mean value of horizontal data		90.079	
Standard deviation of horizontal data		0.11227	
% Deviation respect to nominal data		0.0873%	

OSCAR approach, image change could be identified but vector analysis that indicated direction of change could not be analysed. Moreover, with this system the subject must first be stabilised to avoid any movement of the head, and considerable time is required for digitisation in this system. Yuen et al.[14] used Moire topography to produce contour lines representing the 3D facial shape. However, none of these techniques allows measurement of small face movements after facial reconstructions and no dynamic information about the face movement is provided.

Another way of measuring facial movements is to use facial point systems. Movements of selected points are representative of the movements of the particular face expression. The simplest technique is to hold a hand-held ruler against the patient's face to measure distances. Frey et al. used hand-held callipers to measure the distances between fixed landmarks.[23] With this system the measurement is indirect, the calliper does not provide the direction of movement of the facial point, the angle of movement is very difficult to determine and no dynamic information is available.

Burres[24,25] developed an objective grading system using linear measurements of displacement. Surface electrodes were attached to the midface and aligned horizontally. Surface electromyography recordings were made for each side of the face at repose and during movement, during each of seven standard facial expressions. Distances between specified facial landmarks at rest and during defined facial expressions were also measured with handheld callipers and the differences were converted to percentage of displacement. However, simultaneous multiregional assessments of facial movement could not be performed and the calculations were time consuming and complex. Fields and Peckitt[26] described a simple objective measurement system for facial function that represents function at the mouth as a simple fraction. These authors have chosen to represent facial function as a single expression, the broad smile. The same concept could be applied to other regions of the face, such as elevation of the eyebrow and eye closure. However, this method lacks accuracy and gives no dynamic information about velocity of face movement.

Paletz and Manktelow published a technique that used a camera.[27] This involved a life-size projection of images, representing rest and smile positions that allowed direct measurement of positional changes of points around the mouth. The process only provided useful output concerning the distance and direction of movement but no dynamic information was available, the technique was time consuming and, as the authors pointed out, impractical in the clinical setting.[15]

Wood et al. examined an objective method for measuring facial movement through video micro-scaling.[28] This method superimposes a computer-generated measuring scale over a pre-recorded video image of facial movement to allow digital measurement of facial movement. However, this system has several significant disadvantages. The technique is time consuming because only a single

Table 2 Precision analysis of distances in vertical position

Position	Mean	Deviation	%
1	90.128	0.1336	0.1424%
2	90.175	0.1365	0.1945%
3	90.116	0.3104	0.1294%
4	90.016	0.6050	0.0178%
5	90.242	0.2635	0.2686%
6	90.086	0.1996	0.0958%
7	90.413	0.5656	0.4590%
8	90.197	0.2272	0.2190%
9	90.173	0.2120	0.1923%
10	90.368	0.3564	0.4086%
11	90.038	0.3622	0.0424%
12	90.225	0.1469	0.2499%
13	90.114	0.3658	0.1270%
14	89.956	0.3147	0.0492%
15	89.741	0.3608	0.2881%
16	90.327	0.5756	0.3629%
17	90.118	0.4575	0.1312%
18	90.093	0.2975	0.1033%
19	90.210	0.1163	0.2334%
20	89.988	0.1061	0.0132%
21	90.109	0.1996	0.1216%
Mean value of vertical data		90.135	
Standard deviation of vertical data		0.14839	
% Deviation respect to nominal data		0.1499%	

Table 3 Precision analysis of angles in vertical position

Position	Mean	Deviation	%
1	89.46	0.0659	−0.6014%
2	89.72	0.0399	−0.3143%
3	90.33	0.0322	0.3718%
4	90.05	0.0684	0.0602%
5	90.01	0.0309	0.0059%
6	90.41	0.0258	0.4559%
7	90.45	0.0820	0.5033%
8	90.03	0.0284	0.0297%
9	90.81	0.0510	0.9052%
10	90.30	0.0972	0.3319%
11	90.61	0.0241	0.6724%
12	90.25	0.1369	0.2751%
13	90.64	0.0956	0.7114%
14	89.93	0.0220	0.0770%
15	90.41	0.0451	0.4521%
16	90.64	0.0956	0.7114%
17	90.35	0.0587	0.3893%
18	89.67	0.0541	0.3667%
19	89.51	0.0305	0.5490%
20	89.93	0.0181	0.0795%
21	90.74	0.0199	0.8236%
Mean value of horizontal angles		90.20	
Standard deviation of horizontal angles		0.3958	
% Deviation respect to nominal data		0.2243%	

pair of cursor marks can be superimposed on the video image. The technique requires repetitive data collection with 90° camera rotation for the measurement of vertical distances. Finally, this system yields no information about velocity of movement. More recently, Tomat and Manktelow published a simple system using a video editing programme that overlies frames with the patient again at rest and smiling.[15] The overlaid image is imported into Adobe Photoshop, where measurements are obtained using tools available in the programme. Although the system seems to be simple, the patient's head has to be moved to a semi profile view to capture the z-axis and a central nose point is used as a static reference point to overlay frames to measure the distances. Moreover, the system is time consuming and no dynamic information of movement is shown.

The most sophisticated methods have focused on the computerised measurement of movement of selected landmarks on the face. Sargent et al.[11] used a camera to take a sequence of images of facial expression and transferred them to a computer. These images were overlaid and the movements of selected points were tracked. The results obtained showed that the movement of the oral commisure compared with the apparent area of movement of the face determined by digital subtraction had high intersubject variability. However, no 3D dynamic information is shown with this system. Frey et al. reported a 3D measuring system to track the movements of selected points on the face.[17] This system uses a video camera, precise mirrors, and a customised computer programme. The output includes a graphic display of the movement of points on any two axes, the movement of points over time, and a 3D image of point movement that can be rotated. The main problem with this system is that a specific and complex data analysis must be carried out only in Vienna and the calibration of mirrors is time consuming. Johnson et al.[8] introduced an assay for the simultaneous and multiregional measurement of facial function. This technique involves the placement of dots on selected facial landmarks, the placement of a ruler on the face for calibration, a collection of photographs for the rest position and various facial expressions, the superimposition of a grid on the photographic images, processing of the photographic slide data using a digitisation board, and a handheld puck (mouse) to calculate the displacement of marked positions using a software programme. In addition to the time required to apply this technique, disadvantages include a distortion measurement among photographs of approximately 6%, the inability to measure the temporal parameters of facial movements, and the time consuming method, as it is necessary to use the cursor for selection of facial dots. Wachsman et al.[10] used an automated tracking algorithm, which appears to simplify the analysis proposed by Johnson et al.[8] The automated tracking algorithm system provides x and y coordinates for selected facial points during animation and provides a representation of the actual path of movement. However, with this system no 3D information about movement is shown.

Isono et al.[7] and Linstrom et al.[9,29] describe other more complete and attractive systems for assessment of facial

Table 4 Precision analysis of angles in vertical position

Position	Mean	Deviation	%
1	89.48	0.3292	−0.5831%
2	89.63	0.0337	−0.4114%
3	89.20	0.0370	0.8904%
4	88.67	0.1084	1.4771%
5	89.74	0.0879	0.2919%
6	89.56	0.0610	0.4923%
7	89.98	0.4006	0.0198%
8	89.97	0.0318	0.0304%
9	89.24	0.0332	0.8408%
10	89.78	0.0433	0.2435%
11	89.25	0.1497	0.8350%
12	89.00	0.0557	1.1060%
13	89.75	0.0665	0.2738%
14	89.51	0.0464	0.5456%
15	89.17	0.2016	0.9234%
16	89.51	0.2597	0.5418%
17	90.10	0.1209	0.1109%
18	88.73	0.0360	1.4056%
19	88.93	0.0749	1.1871%
20	89.91	0.0907	0.1001%
21	89.62	0.0373	0.4272%
Mean value of vertical angles		89.46	
Standard deviation of vertical angles		0.4268	
% Deviation respect to nominal data		0.5960%	

movement. Isono et al. presented a landmark-based system in which reflective marks were placed on the face before recording with a video camera. The facial montage consisted of 24 reflective marks. Facial motion was recorded with a video camera at a rate of 30 Hz and 10 frames per individual facial expression were selected for computer analysis. The resulting data points were expressed both as a graphic representation of the facial montage and as a ratio of mean right versus left movements for normal subjects and subjects with facial paralysis. It has built into it an open-ended system to include many more data points for analysis. The graphic representation of a simple fraction of mean right facial movement divided by mean left facial motion over time is an elegant way of demonstrating facial nerve recovery and has intuitive clinical application. Nevertheless, the time lag between analogical capture of the visual movement, digitisation, and graphic display is a temporary delay and, again, no 3D facial movement is showed. Finally, Linstrom et al.[9,29] proposed measures of facial motion using a video-computer interactive system, The Peak Motus Motion Measurement System, to study linear displacement at preselected facial landmarks in the normal and abnormal face. The researcher, using the computer mouse, manually clicks the centre of each marker on each point of interest during the first frame. The Peak Motus software then tracks that point throughout all subsequent frames. The Peak Motus software automatically derives the x and y coordinates for each marker's location. Thus, although dynamic information about facial motion is presented, it is only represented on the x-y axes, as only one camera is used. Moreover, to remove the confounding effect of head motion on the measured displacement of the markers, several manoeuvres are performed. Finally, this system is not a fully automatic system since the observer has to use the cursor to locate the plots for the study, and the analyses are time consuming.

Table 5 Intraclass correlation coefficients (ICC) for testing intrarater reliability

	Rater 1		Rater 2	
	ICC	*P*	ICC	*P*
Vectors				
Frontal (1–5)	0.92	0.009	0.94	0.020
Palpebral (14–16)	0.93	0.020	0.97	0.043
Zygomatic (5–14)	0.90	0.006	0.94	0.006
Angles				
Frontal (1–3–5)	0.91	0.013	0.96	0.019
Palpebral (14–10–16)	0.95	0.013	0.95	0.014
Nasolabial (7–8–10)	0.96	0.004	0.98	0.004
Smile (5–14–15)	0.95	0.004	0.93	0.025
Areas				
Frontal (1–3–5–7)	0.98	0.006	0.99	0.004
Cheek (10–12–5–8–14)	0.99	0.004	0.93	0.001

Numbers aside the name of vectors and angles indicate the number of markers to form the vectors and angles (see Figs. 1 and 6). ICC, Intraclass correlation coefficient.

Table 6 Intraclass correlation coefficients for testing interrater reliability

	ICC	*P*
Vectors		
Frontal (1–5)	0.92	0.004
Palpebral (14–16)	0.92	0.043
Zygomatic (5–14)	0.90	0.031
Angles		
Frontal (1–3–5)	0.90	0.019
Palpebral (14–10–16)	0.97	0.014
Nasolabial (7–8–10)	0.95	0.043
Smile (5–14–15)	0.95	0.025
Areas		
Frontal (1–3–5–7)	0.93	0.014
Cheek (10–12–5–8–14)	0.91	0.007

Numbers aside the name of vectors, angles and areas indicate the number of markers to form the vectors, angles and areas (see Figs. 1 and 6). ICC, Intraclass correlation coefficient.

Our system has advantages compared with the other systems described above. It only needs 20 s for each patient to fully automatically acquire the static and dynamic information about facial motion and generate statistical data. FACIAL CLIMA also provides information for the analysis not only of smile reconstruction but of all kinds of facial movements on all three axes in the same study. Another advantage is that traditional capture systems are said to require slow and tedious calibration processes. However,

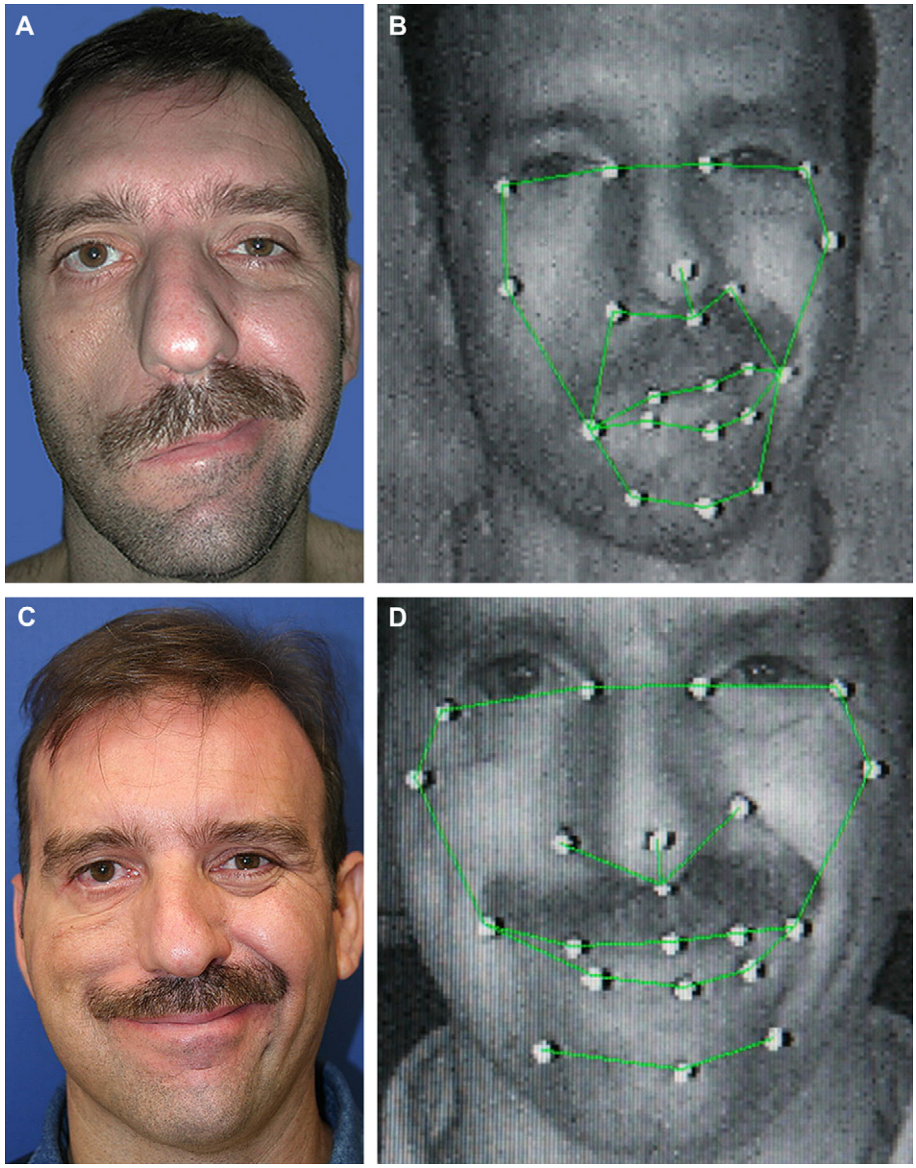

Figure 7 The FACIAL CLIMA has been shown to be valuable for detecting changes in small face movements over time. (A, B) Unilateral facial paralysis patient before smile reanimation surgery with a cross facial nerve graft and muscle transplant. (C) Same patient 2 years postoperatively. (D) FACIAL CLIMA acquisition of data in the same patient.

because of the advanced calibration algorithms used in FACIAL CLIMA, this process has been improved in such a way that a calibration process requires just a few seconds. Moreover, the output represents the distance, angle, velocity and areas at which key points move, which we think is the essential information to compare different techniques in facial reanimation or to follow up neurological disorders affecting the patient's face. Another advantage of FACIAL CLIMA is that with this system it is not necessary to control the head movement of the patient to align any facial points or to record the z axis, as would be necessary using other methods. This system provides complete and accurate information that the surgeon or clinician needs to evaluate the dynamic and static effect of facial paralysis surgery, assess spontaneous regeneration of facial paralysis over time, and evaluate the treatment of neurological disorders affecting the face. With FACIAL CLIMA, surgeons from different centres can compare different techniques by reporting objective, applicable values. It has been demonstrated to be valuable for detecting small changes in facial movement over time (Fig. 7, Tables 7 and 8).

In conclusion, this objective, sensitive and easy to use video-computer method of measuring facial motion has been shown to provide accurate and objective information about facial movement. Its main advantage is its ability to automatically capture and reliably quantify 3D small excursions of movement in the whole face and to describe both the spatial and temporal features of this movement. The patient video can be filmed any time, and can be stored for analysis at a later date. FACIAL CLIMA provides a true automatic measure of the amount, direction and velocity of movement of selected points while capturing movement on the x, y, and

Table 7 Data obtained preoperatively in the patient from Fig. 7

	Mean when contracting (normal side)	Mean when relaxing (normal side)	Mean when contracting (reconstructed side)	Mean when relaxing (reconstructed side)
Vectors (mm)				
Frontal (1—5)	40.1	26.9	38.2	37.8
Palpebral (14—16)	3.4	24.7	15.4	23.3
Zygomatic (5—14)	69.1	82.6	90.5	84.4
Angles				
Frontal (1—3—5)	48.4°	47°	48.4°	47°
Palpebral (14—10—16)	5°	48°	33°	48°
Nasolabial (7—8—10)	126°	110°	111°	95°
Smile (5—14—15)	133°	128°	139°	127°
Areas (mm^2)				
Frontal (1—3—5—7)	1164	1218	1016	1325
Cheek (10—12—5—8-14)	3046	3515	3508	3183
Velocity (mm/s)				
Frontal segment	61	38	2.9	3.6
Palpebral segemt	126	135	49	25
Zygomatic segment	65	46.9	48.1	35.7

z planes in 20 s with complete statistical processing of data. With the use of this system, patients affected with facial paralysis can be compared between surgical centres so that the effectiveness of facial reanimation operations can be evaluated. Moreover, it enables the specialist to assess the effectiveness of treatment for neurological disorders affecting the face. However, we feel that both qualitative and quantitative measurement systems and even the patient opinion are all necessary data to obtain complete information about the effectiveness of a surgical technique for reconstruction of the paralysed face.

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Table 8 Data obtained 2 years postoperatively from the patient in Fig. 7

	Mean when contracting (normal side)	Mean when relaxing (normal side)	Mean when contracting (reconstructed side)	Mean when relaxing (reconstructed side)
Vectors (mm)				
Frontal (1—5)	38.6	25.3	38.5	37.9
Palpebral (14—16)	3.1	24.3	16.6	23.1
Zygomatic (5—14)	65.8	81.5	74.3	84.2
Angles				
Frontal (1—3—5)	49°	44°	48.4°	47°
Palpebral (14—10—16)	5.5°	47°	7°	46°
Nasolabial (7—8—10)	128°	105°	101°	97°
Smile (5—14—15)	133°	128°	132°	125°
Areas (mm^2)				
Frontal (1—3—5—7)	969	1231	1179	1225
Cheek (10—12—5—8—14)	2800	3600	2779	3043
Velocity (mm/s)				
Frontal segment	52	75	2.4	2.1
Palpebral segment	130	142	51	11
Zygomatic segment	60.2	46.6	42.1	30.7

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