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ORIGINAL RESEARCH—FACIAL PLASTIC AND RECONSTRUCTIVE SURGERY

Novel 3-D video for quantification of facial movement

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OBJECTIVES: To evaluate a novel 3-D geometry video acquisition system (3-D VAS) for quantifying facial movement.

METHODS: Ten normal subjects and four patients with facial paralysis underwent recording of facial movement during three facial expressions. Facial feature points of interest were digitally marked on selected images. The maximum 3-D displacement of the brow and oral commissure and palpebral fissure width were determined.

RESULTS: Test-retest reliability using the 3-D VAS in normal subjects was high (Spearman correlation coefficients 0.661-0.830, $P < 0.05$). The predicted ratio of left to right facial measurements was 1.00 in normal subjects, and measured mean ratios were 1.05 (brow excursion), 1.01 (palpebral fissure width), and 1.03 (oral commissure excursion), respectively, matching the prediction. The 3-D VAS reliably quantified facial movement on both sides in patients with facial paralysis.

CONCLUSIONS: The novel 3-D VAS can accurately and reliably quantify facial movement in healthy subjects. It is promising as a clinical tool to quantify facial movement in patients with facial paralysis.

Human facial expression is a rich source of information about a person's psychological, emotional, neurologic, and physiologic state. The loss of facial expression via facial paralysis is a devastating condition, both functionally and aesthetically. Facial paralysis can result from a number of conditions including viral neuropathies (eg, Bell's palsy, Ramsay-Hunt syndrome), trauma, benign or malignant neoplasms, iatrogenic insults, and other infectious etiologies. The incidence of residual facial paralysis is estimated at approximately 127,000 cases annually in the United States, with Bell's palsy accounting for approximately half of these cases.[1] Aside from lack of facial expression, patients have difficulty with speech and articulation, oral competence, and corneal irritation from loss of the blink reflex, which in extreme cases can lead to permanent vision loss. Facial synkinesis is an additional distressing consequence of facial paralysis. It refers to the abnormal involuntary facial movement that occurs with voluntary movement of a different facial muscle group, and it arises from abnormal regeneration of facial nerve fibers to the facial muscle groups. Eye closure occurs with volitional movement of the mouth and midfacial movement occurs during eye closure. There currently does not exist any specific instrument to assess synkinesis objectively.[2] Despite the significant impact that facial paralysis has on quality of life and daily function, there is no reliable, accepted method of quantitatively measuring facial movement.

The current international standard for grading facial movement is a 6-point *subjective* scale adopted in 1985 (House-Brackmann facial grading system).[3] This scale has poor to fair intrarater repeatability and interrater agreement.[4] Although other facial grading scales have been developed to counteract some of the issues with the House-Brackmann scale, they remain subjective measures of facial function that are prone to interrater and intrarater variability.[2] Such subjective measures of facial movement are susceptible to bias, lack precise description of facial dysfunction, and do not describe facial movement impairment according to distinct zones.[5]

There is a significant and increasing need for an objective method of quantifying facial movement.[4,6] Although some authors have attempted to develop objective measures of facial function, none have been adapted for widespread clinical use due to the generally cumbersome, nonautomated modes of recording and analysis.[7-10] In the past 2 decades, the field of facial reanimation has grown considerably and management is usually multi-tiered, with a wide range of treatment options now available including surgical reconstructive procedures, physical therapy/neuromuscular retraining, and medical therapy.[11] Given the varied treatment modalities, objective, quantitative measures of facial movement by zone and measures of synkinesis are ever more critical in permitting health care providers to assess the efficacy of their therapies. Objective measures will also help guide therapeutic decision making by quantifying the disordered facial movement prior to intervention.

Recently, a novel 3-dimensional real-time video acquisition system (3-D VAS) was developed that allows the

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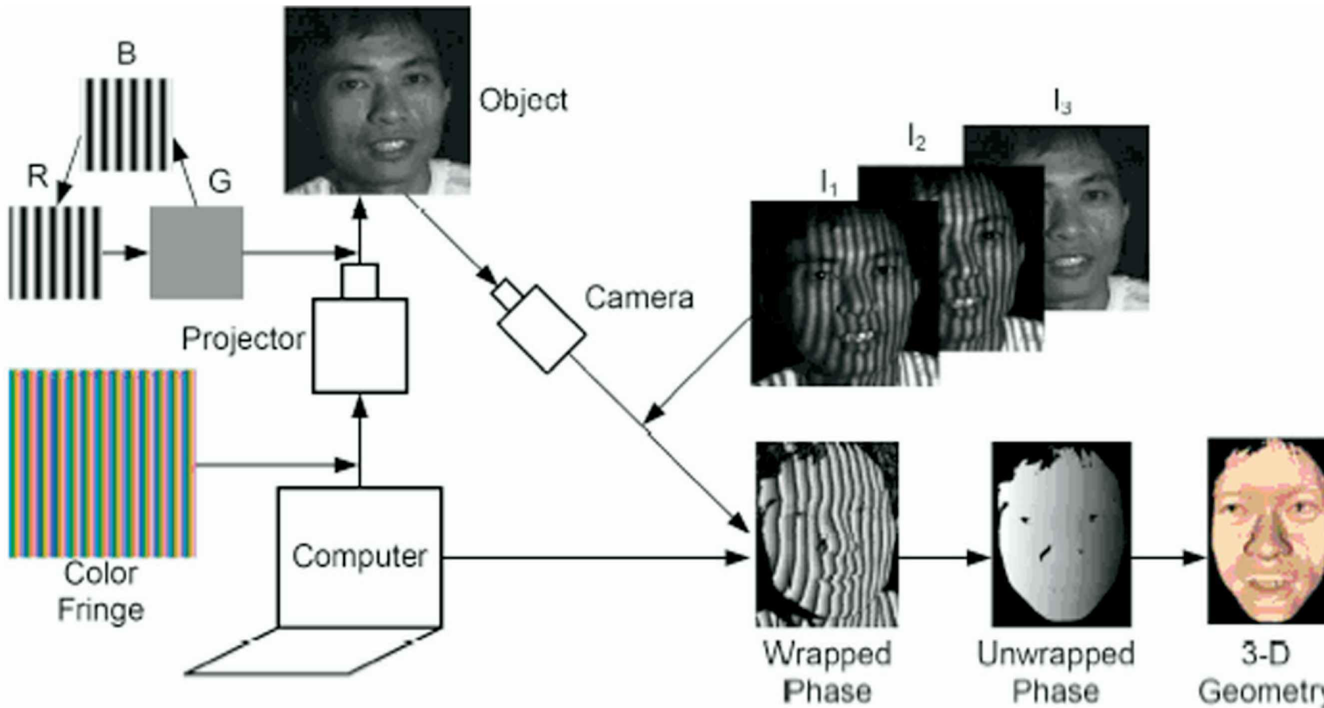

Figure 1 Schematic diagram of the scanner.

measurement of absolute motion of both geometric shapes and positions of deformable objects in real time,[12] and it appears to be well suited to facial movement analysis. The system generates 3-D geometry videos and can measure absolute coordinates of objects pixel by pixel in real time. By utilizing a fast 3-step phase-shifting algorithm,[13] Zhang and Huang successfully developed a real-time 3-D shape measurement system that is able to simultaneously realize acquisition, reconstruction, and display at a speed of up to 40 frames per second (fps) for relative shape measurement.[14,15] This technology has potential utility in a variety of domains including animation, gaming, homeland security, virtual reality, fast prototyping, robotic vision, reverse engineering, industrial measurement, and inspection.

Our goal was to evaluate this 3-D VAS for objective measures of facial movement in a group of healthy subjects with normal facial function and a group of patients with facial paralysis.

METHODS

System Development/Hardware Setup

The high-resolution, real-time 3-D video scanner uses a single-chip digital light processing (DLP) projector and a 3-step phase-shifting algorithm to realize real-time 3-D shape acquisition. Figure 1 shows the schematic diagram of the developed system. A color fringe pattern is generated by a personal computer. When this color fringe pattern is sent to a single-chip DLP video projector, the 3 color channels, or the 3 phase-shifted fringe patterns, are projected sequentially and repeatedly at a frequency of 360 Hz. The color filters on the color wheel of the projector are removed to produce grayscale images. A high-speed CCD camera, synchronized with the projector, is used to capture the reflected fringe images at a frame rate of 180 frames per second (fps). Based on the phase-shifting algorithm used, any successive 3 fringe images can be used to reconstruct one 3-D shape. The 3-D data acquisition speed is 60 fps with a resolution of 640 × 480 pixels per frame.

Subject Recruitment

This study was approved by the Massachusetts Eye and Ear Infirmary Institutional Review Board (IRB). In this pilot study, 10 healthy human subjects without any history of facial paralysis or facial surgery were recruited. Additionally, four patients with varying degrees of facial paralysis were recruited (Table

Table 1
Summary of four patients with facial paralysis recruited for 3-D-VAS analysis

Patient number	Age	Sex	Diagnosis	H-B grade
1	12	M	Iatrogenic facial paralysis (s/p parotidectomy)	III
2	33	F	Bell's palsy—acute	VI
3	31	F	Acoustic neuroma	III
4	72	F	Bell's palsy—delayed recovery with synkinesis	III

Table 2
Test-retest reliability of the 3-D VAS in 10 normal subjects

Mean brow displacement 1	Mean brow displacement 2	Correlation	*P* value
7.88	8.25	r = 0.830	0.013
Mean palpebral fissure width at rest 1	Mean palpebral fissure width at rest 2		
7.60	7.56	r = 0.782	0.019
Mean oral commissure excursion 1	Mean oral commissure excursion 2		
12.04	12.15	r = 0.661	0.048

1). Each subject was recorded using the 3-D video acquisition system while performing three separate facial expressions: brow raise, gentle eye closure, and maximal smile. Each expression was repeated twice. The data were processed manually by selecting the following facial feature points during selected frames from each of the video sequences: 1) right and left brow; 2) width of right and left palpebral fissure; 3) right and left oral commissure; 4) right and left medial canthus (reference points).

The absolute 3-D displacement of the selected facial feature points was calculated and adjusted for head motion by adjusting for motion of the selected reference points (right and left medial canthi).

RESULTS

Normal Subjects—Group 1

Test-retest reliability of the 3-D VAS was determined by calculating the correlation between repeated measures of displacement during each facial expression: brow displacement with brow raise, oral commissure excursion with smile, and palepbral fissure width with eye closure. Test-retest reliability using the 3-D VAS for measurement of all three of the above parameters was high (Spearman rank correlation coefficients 0.661 to 0.830, $P < 0.05$) (Table 2).

A ratio of left to right facial measurements was used to evaluate facial symmetry. The predicted ratio was 1.00 for

Table 3
Absolute 3-D displacement of selected facial feature points in patients with facial paralysis

A. Absolute 3-D displacement of the brow (pixels) on the left and right side for two independent measurements per patient during active brow raise		
Patient #	Brow raise 1	Brow raise 2
1	Left: 2.60/Right 1.28	Left: 3.34/Right 2.13
2	Left 16.27/Right 2.81	Left 15.07/Right 2.96
3	Left 6.10/Right 9.19	Left 2.88/Right 8.08
4	Left 3.65/Right 2.13	Left 7.78/Right 1.02
B. Absolute 3-D palpebral fissure width (pixels) at rest on the left and right side for two independent measurements per patient		
Patient #	Palpebral fissure width 1	Palpebral fissure width 2
1	Left: 10.22/Right 11.37	Left: 10.38/Right 11.72
2	Left 12.57/Right 12.54	Left 13.12/Right 12.44
3	Left 11.79/Right 12.12	Left 10.74/Right 10.74
4	Left 9.02/Right 8.69	Left 7.19/Right 6.64
C. Absolute 3-D oral commissure displacement (pixels) on the left and right side for two independent measurements per patient during active smile		
Patient #	Smile 1	Smile 2
1	Left: 13.34/Right 6.05	Left: 18.14/Right 4.70
2	Left 26.34/Right 2.13	Left 23.3/Right 3.09
3	Left 7.27/Right 23.90	Left 6.04/Right 21.70
4	Left 18.95/Right 7.07	Left 19.36/Right 5.91

the 10 normal subjects, and the measured mean ratios were 1.05 ± 0.13 (brow excursion), 1.01 ± 0.05 (palpebral fissure width at rest), and 1.03 ± 0.07 (oral commissure excursion), respectively, matching the prediction.

Patients with Facial Paralysis—Group 2

The 3-D VAS reliably quantified facial movement on the normal side as well as the paralyzed side in each of the four patients with facial paralysis. Table 3 indicates the absolute 3-D displacement of selected facial feature points during brow raise, eye closure, and smile. The small number of patients in this study precludes any formal statistical analysis. Figure 2 compares measurements of brow displacement, palpebral fissure width, and oral commissure displacement in a patient with complete right facial paralysis (Patient #2) with a normal subject.

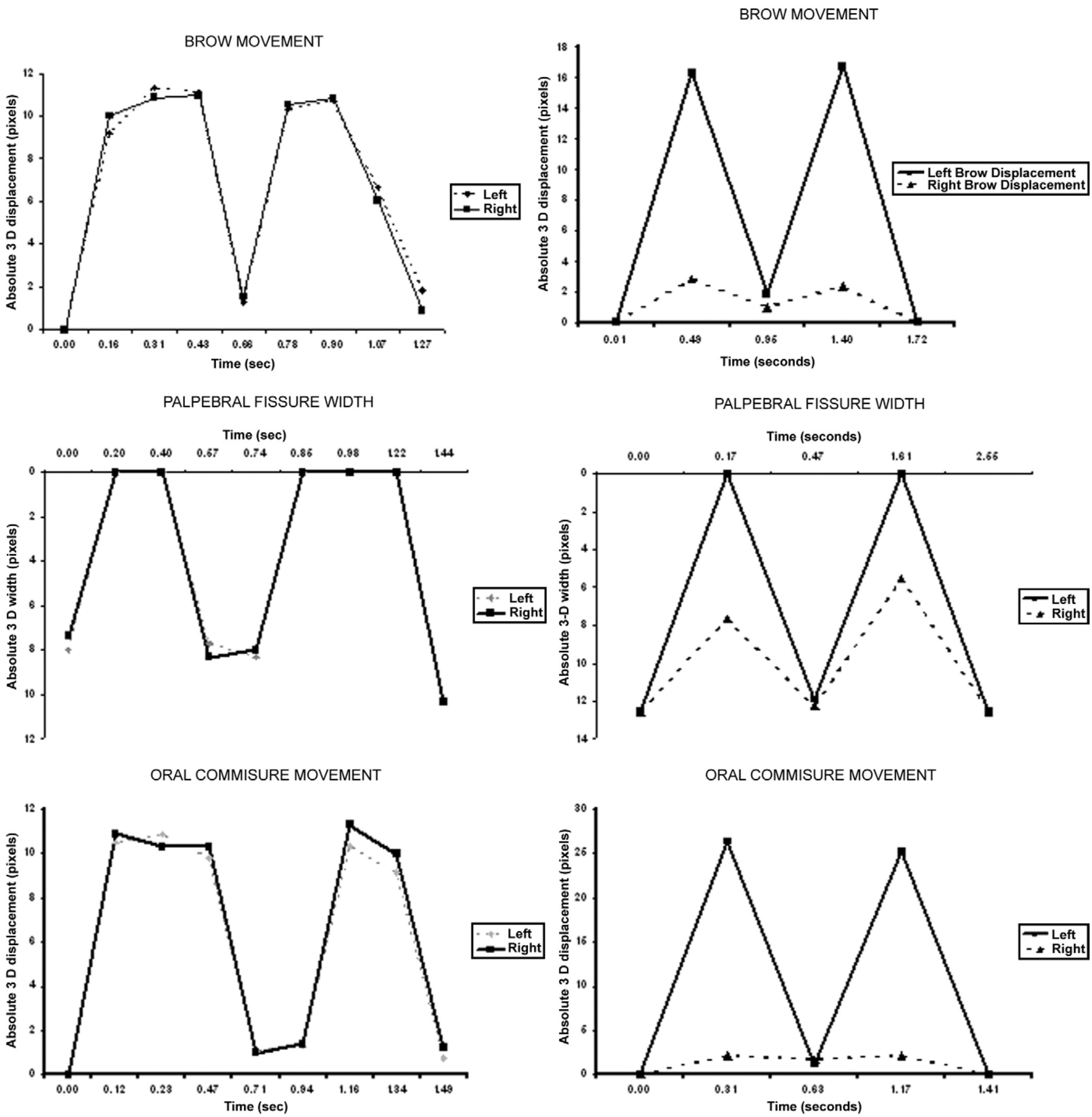

Figure 2 The panels on the left indicate brow displacement, palpebral fissure width, and oral commissure movement in a subject with normal facial function during two successive repetitions of brow raise, eye closure, and active smile. The panels on the right indicate the same movements in a patient with complete right facial paralysis.

DISCUSSION

The novel 3-D VAS can accurately and reliably quantify facial movement in healthy subjects. It is promising as a clinical tool to quantify facial movement in patients with facial paralysis. This study represents the first investigation of a 3-dimensional video capture device to quantify facial movement.

Although there has been a significant amount of work in the arena of facial analysis using computers and video-based analysis, much of this work has focused on the understanding of facial expressions for evaluation of emotion and communication. Most of the systems currently described utilize 2-D video. Given the 3-dimensional nature of facial movement, the 3-D VAS provides a more accurate representation of facial movement. It holds promise for the evaluation of facial paralysis and for patients undergoing facial reanimation surgery as a method of quantifying preoperative and postoperative facial function. This 3-D system may also allow better evaluation of facial expression as it has the capability to measure the depths of various facial creases and wrinkles during facial movement.

The primary limitation of the current study is the low number of patients studied. An additional limitation that is inherent in repeated measures of facial movement is variation in patient effort. However, this study establishes proof-of-concept and provides a basis for further research. Future directions include developing appropriate software to allow for automated analysis of data via automatic tracking of selected facial feature points in 3-D through the entire video sequence. Additionally, we will test the utility of this system for the objective evaluation of synkinesis as well as objective analysis of facial features such as the nasolabial fold depth, which is frequently altered asymmetrically in patients with facial paralysis.

In conclusion, the 3-D VAS is a novel technology that appears to be well suited to measurement of facial movement in normal subjects and patients with facial paralysis. Although it is a promising technique, further research is needed to explore its full potential and automate data analysis.

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FINANCIAL DISCLOSURE

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