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Quantitative analysis of normal smile with 3D stereophotogrammetry — an aid to facial reanimation

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Summary *Introduction:* Rubin observed that there was a great deal of variation in smiles. [Rubin LR. The anatomy of a smile: its importance in the treatment of facial paralysis. *Plast Reconstr Surg* 1974;**53**:384–7] Smile reconstruction requires an understanding of the facial movements that occur during a normal smile. Facial reanimation should be tailored for each individual patient so that the movements on the reconstructed side are similar to that on the normal side.
Aim: The aim of this study is to produce a quantitative analysis of smiles, as a basis for smile reconstruction and to compare our subject's smiles to the classification suggested by Rubin.
Method: The smiles of 71 volunteers were analysed using three-dimensional (3D) stereophotogrammetry in *x*, *y* and *z* vectors. Each subject had the distances and angles of 10 surface landmarks (cheilion left and right (L&R), labiale superius/inferius, mid-lateral upper/lower lip (L&R), nasolabial fold (L&R)) moved from the relaxed position to that in a maximum smile. All subjects' smiles were classified into the Rubin subtypes of corner of the mouth, canine and full-denture smile.
Results: The average distances and angles moved by oral landmarks during a smile in a 3D plane were — cheilion: 16.6 mm at 31°; labiale superius: 8.2 mm at 31°; upper mid-lateral lip: 10.5 mm at 25°; labiale inferius: 5.3 mm at −56°; lower mid-lateral lip: 7.8 mm at 41° and nasolabial fold: 12.6 mm at 33°. Our population results for the smile subtypes suggested by Rubin were — corner-of-the-mouth smile: 77%, canine smile: 15% and full-denture smile: 8%.
Conclusion: Our study offers a simple quantitative method for measuring the smile to assess the outcome of reanimation surgery between different surgical procedures and units. Proportions of our study group with corner-of-the-mouth, canine and full-denture smiles were consistent with Rubin's study.

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A smile can express a whole host of emotions, ranging from the warmth of contentment, joy, delight and affection to arrogance and bafflement. Facial expression is an important part of human communication. As a result, an inability to produce facial expressions leads to communication difficulties. Patients with facial paralysis are thus hindered in the communication conveyed by facial expression.

There is a great deal of variation in smiles and, if we are to achieve optimal results in facial reanimation and smile reconstruction, we should attempt to tailor the operation for each individual patient such that the movements on the reconstructed side are similar to that on the normal side.

There are a variety of surgical techniques that can aid the facial-palsy patient. The surgical method used depends upon the cause, the degree and the length of time of facial paresis. The potential surgical methods which have evolved over the past 30 years are primary or secondary nerve repair,[2] interpositional nerve graft,[3] cross-face nerve graft,[4,5] hypoglossal-nerve transfer,[6] masseter or temporalis muscle transposition[7] and free muscle flap.[8–11]

Free muscle transfer allows the plastic surgeon to create a dynamic reanimation of the paralysed face and the formation of the smile. Within various constraints, it has become feasible to place the free muscle transfer into the face and vary direction, amount of movement and attachment of the muscle as desired.[8,12,13] With greater choice of reconstructive potential, it has become progressively more valuable to know about the shape and movements of a normal smile.

Various authors[1,14,15] have discussed the anatomical movements of the mouth during smiling and the resultant effect of dental exposure. Rubin was the first author to take an interest in smile and observed that there were different anatomical smiles – each varying with the strengths of the surrounding perioral muscles.[1] He recognised that these anatomical differences were important in the treatment of facial paralysis and classified smiles into three basic forms: the corner-of-the-mouth smile (Mona Lisa smile), the canine smile and the full-denture smile. In addition, he noted that muscle, soft-tissue and bony anatomical variations can influence the smile. For a smile to be natural and normal the muscles attached to the lips and nasolabial fold should contract in an orderly fashion.

Although simple measurements of normal smiles have been carried out by several authors, certain ambiguities and technical limits have caused deviations from accurate data. Paletz et al.[13] measured distances with a simple ruler on the skin surface to describe the smile, although this is time consuming. All the other regions of the face were not included, and reliable measurements were obtained. Dong et al.[16] measured the movement directly against the subject's face with mask rulers. This procedure can lead to errors in measuring the direction of movement, and it is difficult to sustain a full smile while measurements are taken.

The key purpose of treating facial paralysis is to restore muscle activity. In unilateral facial paralysis, the aim is to restore a balance with the normal unaffected side. When planning facial reanimation surgery, the surgeon should have a clear understanding of the facial movements in the patient's smile. This information should be quantitative about the movement of various oral landmarks and the angle in which they move.

In patients with bilateral facial paralysis, such as Mobius syndrome, there is no guide to the oral movement during a smile, and it would be useful to know quantitative data regarding the three-dimensional (3D) movement of the smile in normal individuals to aid reconstruction in this patient group. Finally, it is important to evaluate the variety of facial reanimation operations pre- and postoperatively with an objective and quantitative method for analysis.

One such objective and quantitative method for analysing facial movement is 3D stereophotogrammetry.[17] This system uses two digital camera pods to create a 3D facial image. Thus, the aim of this study is to analyse the quantitative movement of a normal smile using 3D stereophotogrammetry in Caucasians so as to aid any future facial reanimation.

Method

Our study included 71 healthy Caucasians (38 males and 33 females) of an average age of 34 years (range: 21–59 years). All subjects had full dentition, normal maxillary/mandibular relationships and no previous history of any facial nerve paralysis. Written and verbal information was given to all subjects, and written consent was obtained prior to commencing the study. This study was approved by a local ethics committee.

Each subject was imaged using the VECTRA-3D 2 dual module system (Canfield Scientific, Inc., Fairfield, New Jersey, USA), which uses stereophotogrammetry (Figure 1). The 3D stereophotogrammetry was supplied by Surface Imaging International Ltd, UK.

The 3D stereophotogrammetry system integrates two pods, each with three cameras; on either side, two monochrome cameras are synchronised to capture images illuminated by integral projectors. This camera system required calibration each day prior to capturing the facial data. The 3D facial model that is generated can be analysed using VAM® (visualisation, analysis and measurement) application software. As it is a digital facial model, one is able to rotate, pan or zoom into the images, as well as view multiple surfaces simultaneously to facilitate analysis.

The subjects were imaged with the mouth in the closed, relaxed position and in the widest smile possible (with lips apart). Smiles were spontaneous in response to spoken and visual stimuli provided by the first author. All of their recordings were completed, and images were analysed by a single investigator. Each facial landmark was plotted on a 3D image created by the software according to those described by Farkas[18] and others.[12,13,19] For each subject, the following landmarks were placed: right and left cheilion (chR and chL), labiale superius (ls), labiale inferius (li), nasolabial fold (nlf), right and left upper middle lateral (umlR and umlL), right and left lower middle lateral (lmlR and lmlL) in the resting lip position and at maximal smile (Figure 2). Each landmark had its vector distances measured in the x (horizontal plane), y (vertical plane) and z (dorso-ventral plane). This enabled us to calculate

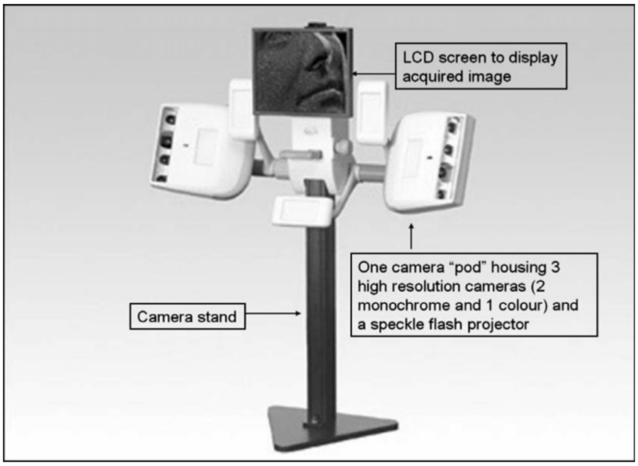

Figure 1 Stereophotogrammetry System VECTRA-3D dual module system.

distances and directions moved in two-dimensional (2D) and 3D planes (Figure 3).

The second part of this project was to compare the smiles of our subjects in a similar way to Rubin 1974,[1] and we classified them into three types of smile.

Intra-rater and inter-rater reliability of VECTRA 3D

For assessment of intra-rater reliability (re-test reliability), facial landmarks were completely removed and re-plotted on three separate occasions. Intra-class correlation was used in order to assess the re-test measurements. To assess the measurement between raters (agreement between raters) intra-class correlation was used. The question we answer here is whether the observers performing these measurements are similar.

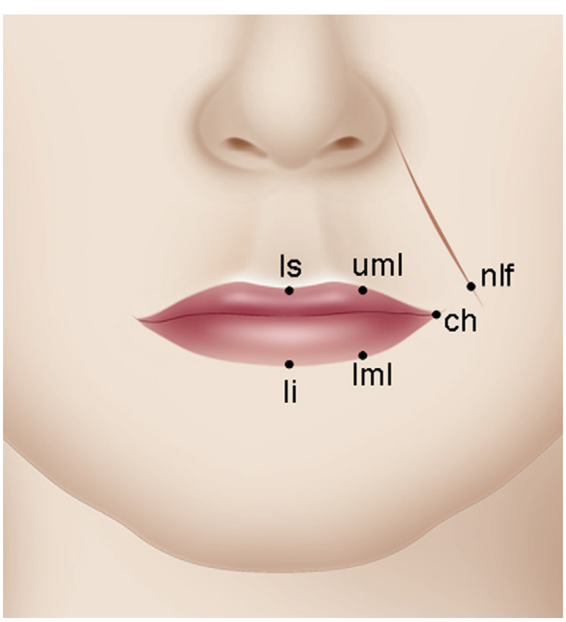

Figure 2 The landmarks used in this study.

Figure 3 Movement of the cheilion in the *x* (horizontal plane), *y* (vertical plane) and *z* (dorso-ventral plane) are vectors during smile. Note that distance A refers to the distance moved in a three-dimensional plane and that distance B refers to the distance moved in a two-dimensional plane. β refers to the angle of movement in a three-dimensional plane and α refers to the angle of movement in a two-dimensional plane.

Results

The mean movement of each landmark was measured as *x*, *y* and *z* vectors. The original vectors for *x*, *y* and *z* were 0, 0 and 0 when in the resting, closed-mouth position. Mean vector movement from the resting position to a full smile with teeth showing is depicted in Table 1. There were distinct patterns for movement of all the landmarks investigated. The cheilion, upper mid-lateral lip and nasolabial fold all moved laterally, superiorly and posteriorly with smiling. The labiale superius moved superiorly and posteriorly and, conversely, the labiale inferius moved inferiorly and posteriorly. Interestingly, the lower lip mid-lateral landmark moved laterally, posteriorly and, on average, inferiorly (although in several patients it moved superiorly).

The right and left cheilion, upper mid-lateral, lower mid-lateral and nasolabial fold had comparable movements.

From the *x*, *y* and *z* vectors, distances and angles in a 2D and 3D approach can be calculated (A, B, α and β) (See Figure 3 for an explanation of A, B, α and β parameters). The results of angles and distances of each landmark are

Table 1 Average vector movement of oral landmarks during a normal smile from the resting oral position

Landmark	Average vector movement from resting position to full smile (mm)		
	x	*y*	*z*
Cheilion (Right and left)	7.6	8.6	12
Labiale superius	−0.1	4.2	7.0
Upper Mid-lateral lip (Right and left)	4.1	4.5	8.6
Labiale inferius	0.1	−4.4	2.9
Lower Mid-lateral lip (Right and left)	4.1	−0.7	6.6
Nasolabial fold (Right and left)	6.9	6.9	8.0

Table 2 The distances and angle of movement of oral landmarks during a smile in two-dimensional and three-dimensional planes

Landmark	Average angle and range (degrees)	Average angle and range (degrees)	Average movement and range (mm)	Average movement and range (mm)
	A	β	A	B
Cheilion (Right and left) Figure 4	48 (20–59)	31 (19–61)	16.6 (7–24)	11.4 (8–16)
Labiale Superius Figure 5	90 (75–105)	31 (22–41)	8.2 (3–13)	4.2 (2–6)
Upper Mid-lateral Lip (Right and left) Figure 6	47 (23–64)	25 (19–36)	10.5 (4–16)	6.0 (4–12)
Labiale Inferius Figure 7	−90 (−72–−110)	−56 (−32–−78)	5.3 (4–10)	4.4 (2–6)
Lower Mid-Lateral Lip (Right and left) Figure 8	−9 (47–−36)	41 (22–50)	7.8 (2–11)	4.1 (2–8)
Nasolabial fold (Right and left) Figure 9	45 (23–69)	33 (26–42)	12.6 (4–17)	9.7 (8–15)

shown in Table 2. Illustrations to show landmark distance and angle of movement in a 2D plane are shown in Figures 4–9.

Landmark movement was, on average, reduced in the female group as compared to males by around 5–15%. However, there was no significant difference using the Student *t*-test in any of the landmarks (significance considered at $p < 0.05$). The directions between males and females were also similar.

All except one of the 70 subjects who were analysed showed near-symmetrical movement of the left and right sides of their faces. Landmark variation between the left and right varied by 0–6 mm, and the direction of movement varied to a maximum of 10°.

The results of the smile subtypes suggested by Rubin are shown in Table 3. The Figures 10, 11 and 12 show examples of corner-of-the-mouth smile, canine smile and full-denture smile for the population, respectively.

Intra-rater and inter-rater reliability of the VECTRA

The intra-rater reliability for measurement of facial-landmark movement and angles was found to be highly accurate, with an intra-class correlation coefficient of greater than 0.93 for both raters. Similarly, the inter-rater reliability for measurement of landmark movement and angles was again found to be highly accurate, with an intra-class correlation coefficient of more than 0.92.

Figure 4 Illustration to show the two-dimensional distance and direction of landmarks that were measured: Cheilion.

Discussion

There are numerous treatment options for patients with facial paralysis. The aetiology, extent and duration of facial-nerve dysfunction and the state of the muscle often determine the best method of reconstruction. The options available for facial reanimation include primary or secondary nerve repair,[2] inter-positional nerve graft,[3]

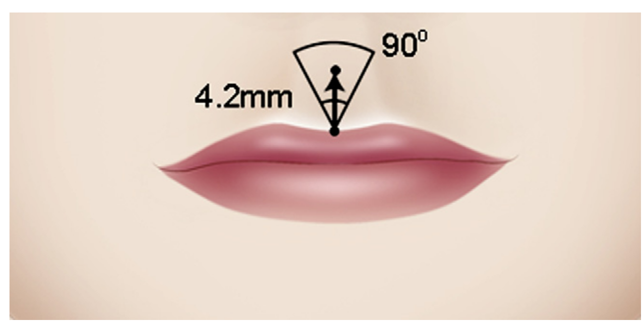

Figure 5 Illustration to show the two-dimensional distance and direction of landmarks that were measured: Labiale superius.

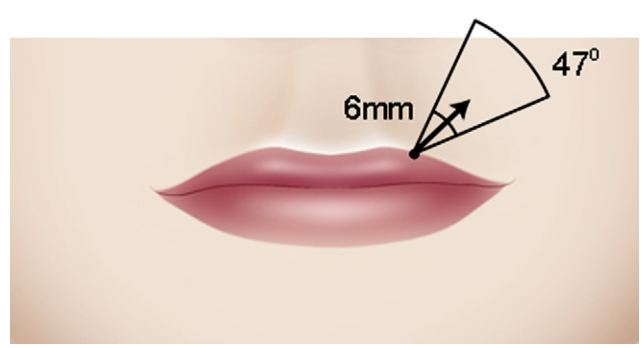

Figure 6 Illustration to show the two-dimensional distance and direction of landmarks that were measured: Upper mid-lateral lip.

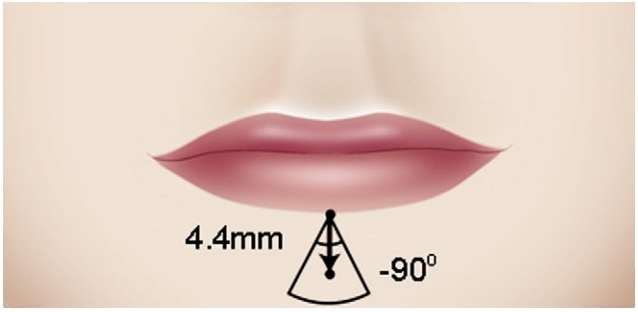

Figure 7 Illustration to show the two-dimensional distance and direction of landmarks that were measured: Labiale inferius.

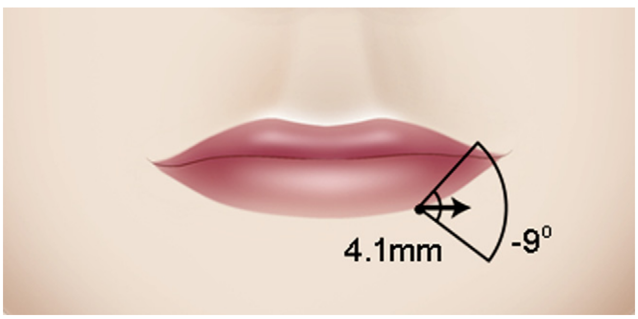

Figure 8 Illustration to show the two-dimensional distance and direction of landmarks that were measured: Lower mid-lateral lip.

cross-face nerve graft,[4,5] cranial nerve transfer,[6] regional muscle transposition[6] and free muscle flap.[9,11]

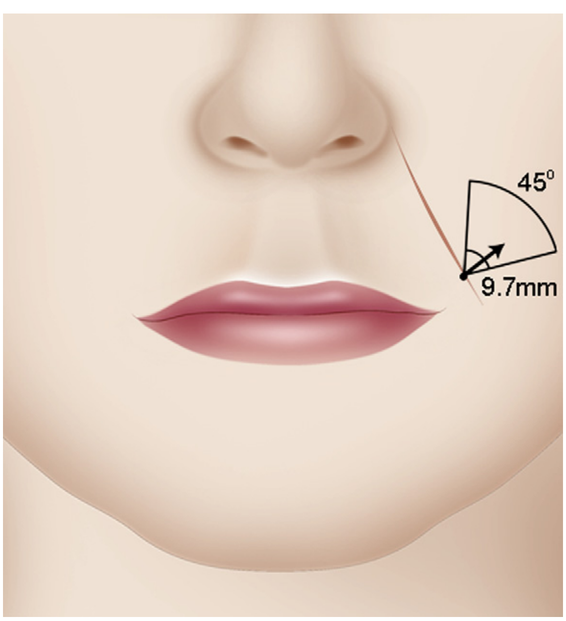

Figure 9 Illustration to show the two-dimensional distance and direction of landmarks that were measured: Nasolabial fold.

Table 3 Results of our population classified in to Rubin subtypes

Smiles type	Percentage of our population
Corner-of-mouth smile (Mona Lisa Smile) Figure 10	77
Canine smile Figure 11	15
Full-denture smile Figure 12	8

The aims of the surgeon in facial reanimation are to support the mouth at rest and to provide animation to the mouth and cheek. The origin, insertion, tension and location of the free muscle can be wherever the surgeon deems it will successfully generate a smile. However, in practical

Figure 10 Examples of a corner-of-the-mouth smile (Mona Lisa Smile).

terms, a muscle flap will produce a unidirectional vector with maximal movement at the cheilion.

Each person has a unique smile. The shape of the smile is determined by the exposure of the red vermillion, the amount of teeth displayed and the direction and quantity of the movement of the cheilion and upper middle lateral lip. In addition, the presence, extent and position of the nasolabial fold and the presence or absence of depressor labii function also create a distinctive smile.

Anatomical classifications have been suggested for describing the smile.[1,14,15] Rubin classified smile into three anatomical types.[1] As part of our study, we did a simple correlation of the anatomy of the smile and classified it in the same way as Rubin. In Rubin's study, 67% had a corner-of-mouth or 'Mona Lisa' smile, 31% had a 'canine smile' and 2% had a 'full-denture' smile. Our results were 77%, 15% and 8%, respectively. It is impossible to exactly reproduce the method of Rubin since he did not, in fact, state his method or the ages of subjects in his seminal paper. However, the canine smile (where the levator labii superioris is dominant, initially contracting first exposing the canine teeth, followed by the corners of the mouth contracting to pull the lips upwards and outwards) is quite a subtle smile, and there is a significant overlap with the corner-of-mouth smile (Mona Lisa smile). This may have been one reason why we had slightly different proportions in our group compared to Rubin's group.

We believe it is essential to thoroughly investigate and measure the patient's smile on the non-paralysed side. This evaluation gives the surgeon an opportunity to consider the shape of the smile that is required on the paralysed side and to look at the strength of the smile. Thus, a dynamic reconstruction is designed for each individual patient.

Previous attempts at trying to quantitatively analyse the normal smile have used time-consuming techniques and relatively small numbers of subjects. Paletz et al. used a movie camera to record smiling and then projected the images onto a blank sheet of paper to record the smile movement.[13] This method is not particularly practical in a clinical situation. In addition, this technique only analysed smile in a 2D plane (*x* and *y* only), which gives inadequate description of a real smile. In fact, Gross et al., in 1996, showed that 3D amplitudes were significantly larger than 2D amplitudes.[20] They found that 2D amplitudes underestimated 3D measurements by as much as 43%. A similar method to that used by Paletz using a ruler directly against the subject's face was used by Dong et al., in 1996, for analysing Korean smiles.[21]

Frey et al., in 1999, produced a method of analysing facial movement using a digital video camera and two mirrors and a customised computer program. Although this system is highly accurate, its disadvantages include: the subjects had to be marked with a water-resistant ink for the facial movement to be measured, and the method is time-consuming and complex.[22]

Linstrom used a computer interactive system, 'The Peak Motus Motion Measurement System', to study linear displacement at preselected facial landmarks which required the application of plastic craft beads wrapped in reflective tape. This technique requires the investigator to click with a computer mouse on each landmark during the first frame and the Peak Motus software tracks that point through subsequent frames. This system requires specialised equipment and is not fully automatic and is time consuming. In addition, this system only gives *x*- and *y*-axis landmarks of facial motion as only one camera is used, and therefore true 3D landmark motion is not possible.[23,24]

Figure 11 Example of a canine smile.

Tomat and Manktelow used a relatively simple technique requiring the application of a water-soluble pencil to place facial landmarks, as well as a 1-cm ruler and video recording of the patient while performing maximal-effort smiles. Then, using a video-editing program, one frame showing the patient at rest is overlaid with a second frame showing the patient's smile. The disadvantages of this study are that the central nose point was used as the static reference point, and it has been the observation during other studies using the VECTRA that the central nose point moves during the smile in both the *y* and *z* vectors and the

Figure 12 Example of a full-denture smile.

patient is required to keep still during the recording to keep this point fixed.[19]

Kang et al. analysed the 3D smile of 50 Oriental volunteers using a digital video camera. This method required stabilisation of the head using a rest in the Frankfort horizontal plane and required a set distance between the camera and the subject.[12] The disadvantage of this method is that it is time consuming and can lead to inaccuracies if there are changes in the subjects' head position or distance from the camera.

A 3D capture system of facial movements 'FACIAL CLIMA' was recently published. This is an automatic optical-motion system which uses video recording with three infrared cameras, but requires placing reflective dots on the subject's face which can interfere with the facial movements and a relatively long capture process which can take up to 1 min.[25]

Despite there being a number of facial-movement-assessment techniques, none have been adopted for widespread clinical use. The advantages of the 3D VECTRA are that it produces a digital facial model where one is able to rotate, pan or zoom into the images, as well as view multiple surfaces simultaneously to facilitate analysis and, although not used in this study, one can also calculate volumes (e.g., lower lip volume), surface areas and surface distances. Furthermore, our system of 3D VECTRA 2 has several other advantages over the previously described techniques. The 3D stereophotogrammetry is independent of head posture, does not require the patient to be at a set distance from the cameras, one can plot facial landmarks on a 3D image created by the software rather than applying ink or other techniques directly to the subjects' face (a disadvantage of many of the older techniques) and images are taken within 2 ms. In addition, the VAM software can easily determine measurement and angles by simply placing landmarks on the face and is user friendly. Finally, all standard views in repose are captured simultaneously from a single 3D image. In essence, this system provides the surgeon or researcher with all the necessary data required to assess the facially reanimated patient, as well as assessment of the recovery of facial paralysis. The VECTRA 2 is available for US$45 000 (UK£ 30 000).

Both intra-rater and inter-rater reliability of the VECTRA has been proved to be highly accurate.

Our results show that the movement of not only the cheilion, but also the nasolabial fold and upper mid-natural lip were predominantly lateral, superior and posterior. These movements are because the dominating muscle in their movement is the zygomaticus major. This suggests that the surgeon should not only concentrate on the movement of the cheilion when placing free muscle transfers into the perioral region, but also create lift and lateral movement to the upper mid-lateral lip. If the muscle transfer is only inserted into the cheilion, then this will not re-create the smile but rather cause the drooping of the central part of the upper lip.

Although our results suggest that the cheilion and nasolabial fold move in the same direction, the cheilion moves, on average, 4 mm more. As a result, the cheilion and nasolabial fold come closer together in a smile. Thus, from a technical point of view, the surgeon should concentrate on positioning free tissue around the site of the cheilion since this will also create passive movement of the nasolabial fold. Positioning the free muscle fixed to the nasolabial fold only will not reproduce the reduced gap that occurs between the cheilion and the nasolabial fold during the normal smile.

The labiale superius movement is predominantly superior as the predominant muscle in this movement is the levator labii superioris. The labiale inferius movement is principally inferior and is mainly acted on by the depressor labii inferius. The lower mid-lateral landmark varies considerably from patient to patient, always moving laterally and posteriorly, but varying in whether it moves inferiorly or superiorly. This landmark is under the influence of the zygomaticus major and also the depressor labii inferius, and it seems that the predominating muscle determines its direction. The fact that there is some inferior movement of the lower lip during a normal smile is obviously a problem in reconstruction, since surgeons tend to only consider the upwards, lateral and posterior movement of the cheilion. Facial reanimation surgery is challenging and creating an inferior movement of the lower lip would make a complex procedure all the more difficult. It would seem that most of the current reconstructive techniques would result in the lower mid-lateral lip being in a more superior position than would occur during a normal smile. Paletz has suggested that one way to overcome this is to resect the depressor labii inferioris on the normal side, thus balancing the face and creating symmetry.[13]

Our results showed that the cheilion had the greatest movement, with an average of 16.6 mm in the 3D plane. A significant amount of movement was also seen by the nasolabial fold (12.6 mm). In addition, it is noteworthy that both these landmarks had similar angles of movement, which can be explained by their close proximity and also that they are subject to similar muscular forces. As can be seen from the tables, there is a great variation between normal individuals in the amount of movement of individual landmarks. Again, the greatest variation was seen in the cheilion; here individuals ranged from 7 mm to 24 mm of movement in the 3D axis. This variation of almost 350% shows the importance to the surgeon of looking at individual smiles (or the non-paralysed side) prior to facial reanimation surgery.

Our results are similar to those produced in other papers, for example, the cheilion movement in our article was 16.6 mm at an angle of 48° in the 2D plane. Paletz et al. showed on average that the cheilion moved 14 mm at 40°.[13] Similarly, Kang showed that the cheilion moved 13.7 mm at 52° on average.[12] Our results are similar to Kang et al., although in our Caucasian study the landmarks moved greater distances on average than those in Kang's Oriental population during a smile. This is consistent with the results of Tzou et al., in 2005, who showed that, in general, Europeans have larger facial movements that Asians by up to 37.1%.[26]

All of the 70 subjects analysed showed near-symmetrical movement of the left and right sides of their face. Landmark variation between the left and right sides varied by 0—6 mm, and the direction of movement varied to a maximum of 10°. This shows that there is a variation between the landmarks on the left and right sides of the face. However, these variations are apparently not obvious during normal social interaction. There was, however, one subject (excluded from the 70 subjects analysed) who had asymmetrical movement of the lower mid-lateral lip (the rest of the smile was normal). There was a difference between the left and right side of around 10 mm. This subject had no previous facial surgery or facial paralysis. This asymmetry was not obvious in normal interaction and during smiling. She did, however, mention that she had observed this deficit whilst looking into the mirror previously.

We found that landmark movement was greater in the male group as compared to female group by an average of around 5–15%, but there was no significant difference. Previous research into facial movements[22,27,28] has shown that men have statistically significantly larger facial movement than women. These differences are likely to be due to the larger growth of the male facial musculature compared with those of females.

One of the potential problems of analysing the movements of the normal side of a patient with facial paralysis is that the normal side shows increased movement, because it is unopposed by the paralysed side. However, this at least gives the surgeon some indication of the angle of movement of landmarks and the distance which it moves. In addition, if there is significant inferior movement of the lower mid-lateral lip on the normal side, then the surgeon could consider a procedure on the normal depressor labii inferioris.

In addition, the aim of this study was to quantitatively analyse oral landmark movement during a normal smile using stereophotogrammetry. The data obtained can then be used in future facial reanimation surgery. This study highlights that surgeons who are considering facial reanimation surgery on a patient should consider quantitative analysis of the normal-side smile to aid reconstruction of the paralysed side. Furthermore, this study highlights the anatomy of a normal smile which the plastic surgeon should try to re-create. Although it may be difficult to reproduce the exact movement distances of the normal side, it may be possible to orientate any free muscle transfer at a certain angle and insert it into the cheilion, rather than into another perioral landmark.

In conclusion, we have found that the 3D stereophotogrammetry is a quick, non-invasive tool which allows accurate measurement of 3D movement of facial landmarks and that such a system can be used as an objective system to evaluate the effectiveness of different facial reanimation procedures. In addition, our results of normal subjects could be used in patients with bilateral facial palsy, such as in Mobius syndrome, to re-create their smile.

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