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Research Paper
Imaging

Fluctuating asymmetry of dynamic smiles in normal individuals

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Abstract. The aim of this study was to quantify the fluctuating dynamic facial asymmetry during smiling in a group of 'normal' adults, using three-dimensional (3D) motion facial capture technology. Fifty-four male and 54 female volunteers were recruited. Each subject was imaged using a passive markerless 3D motion capture system (DI4D). Eighteen landmarks were tracked through the 3D capture sequence. A facial asymmetry score was calculated based on either a clinically derived midline or Procrustes alignment; scores were based on the Euclidean distance between landmark pairs. Facial asymmetry scores were determined at three time points: rest, median, and maximum frame. Based on the clinically derived midline and on Procrustes alignment, the differences between male and female volunteers, as well as those at the three different time points, were not clinically significant. However, throughout a smile, facial and lip asymmetry scores increased over the duration of the smile. Fluctuating facial asymmetry exists within individuals, as well as between individuals. Procrustes superimposition and the clinically derived midline produced similar asymmetry scores and both are valid for symmetrical faces. However, with facial asymmetry, Procrustes superimposition may not be a valid measure, and the use of the clinically derived midline may be more appropriate, although this requires further investigation.

Key words: stereophotogrammetry; dynamic; 3D motion capture; normal; 4D; adult; fluctuating asymmetry; Procrustes.

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Facial attractiveness and beauty are important underlying psychological cues in judging an individual's health. Evolutionary psychology proposes that there are four main cues that determine facial attractiveness with respect to mate preference; these are averageness, symmetry, youthfulness, and sexual dimorphism[1]. Facial symmetry, from a clinical perspective, is probably best thought of as 'reflection symmetry', where features of the face do not change on reflection. Perfectly symmetrical faces do not occur naturally and there is a baseline level of symmetry or 'fluctuating asymmetry' between individuals, which is characterized by small random deviations from perfect bilateral symmetry[2]. Individuals with a marked facial asymmetry are known to have a lower quality of life[3]. Hence one of the aims of facial reconstructive surgery and orthognathic surgery is to minimize facial asymmetry and to correct any clinically significant facial asymmetry, respectively. As well as assessing pan-facial symmetry, the symmetry of specific facial regions has been reported, for instance the nasolabial region in cleft lip and palate patients[4], the mandible in orthognathic patients[5], the nose in rhinoplasty patients, and the orbits in cranial abnormalities. It is crucial that the clinical team is aware of the site and severity of the asymmetry in comparison to a 'normal' group before embarking on surgical correction of the facial deformity.

Previously, the assessment of static facial symmetry (at rest) in a normal group of individuals has been based on two-dimensional (2D) images, using angular and linear measurements[6] and statistical shape analysis[7]. The introduction of three-dimensional (3D) imaging has allowed further comprehensive evaluation of static facial symmetry. A recent study assessed the 3D facial symmetry of 20 male and 20 female 'normal' individuals at two discrete time points, i.e. at rest and at maximum smile[8]. The study found a statistically significant higher asymmetry score at maximum smile than at rest based on 27 landmarks. Rather than assessing the expression at rest and maximum smile, dynamic facial asymmetry assessment over the entire smile should be the gold standard. Recently, this has been addressed in part in a comparative study of a small group of non-cleft controls ($n = 11$) and patients with repaired unilateral cleft lip and palate ($n = 12$) using 3D motion capture technology[9]. However, only the motion of the upper lip was assessed: at the oral commissure, within the cupids bow, the cupids bow peak, upper lip lateral to the cupids bow, and the mid philtral ridge. Although these studies have provided some limited information, they have either failed to capture the true dynamic nature of smiling or have presented limited data.

The development of 3D motion capture technology has allowed the capture of non-verbal expressions from rest to maximum expression. To assess reflective symmetry, the left and right sides of the face need to be reflected or mirrored around a midfacial plane. The midfacial plane can be determined clinically on the basis of anatomical landmarks, or can be derived mathematically[10]. The latter analysis is based on Procrustes 'best-fit' superimposition, where distances between the original 3D landmark configuration and their mirror image can be calculated and expressed as an 'asymmetry score'[11,12].

The aim of this study was to quantify the fluctuating dynamic facial asymmetry during smiling in a group of clinically 'normal' Caucasian adult males and females, using 3D motion facial capture technology. The null hypothesis was that there is no difference in the magnitude of overall facial asymmetry, based on the asymmetry score, between the genders. In addition, the effects of using a clinically or mathematically derived midline were investigated.

Materials and methods

Sample size calculation

A pilot study was undertaken to determine the asymmetry scores of a group of seven volunteers with a clinically significant asymmetric smile (assessed by BSK and CJL) and seven individuals with a clinically symmetrical smile. A difference in asymmetry scores of 0.5 determined the threshold of clinical significance. This together with a standard deviation (SD) of the differences of 0.7, power of 0.8, and statistical difference of 0.0035, following a Bonferroni correction for multiple testing, resulted in a minimum sample size requirement of 43 individuals per group.

Subjects

Ethical approval for the study was obtained from the Dental Research Ethics Committee (DREC) at the University of Leeds, UK. Fifty-four male and 54 female volunteers were recruited to take part in the study. Volunteers were recruited if they met the following inclusion criteria: they were between the ages of 18 and 40 years, had undergone no previous facial surgery, and had no lip piercing, history of facial trauma, or neurological facial problems. In addition, subjects recruited were clinically symmetrical and had class I incisors, as judged by a single experienced consultant NHS orthodontist and an orthodontic trainee.

Imaging using DI4D Pro passive stereophotogrammetry capture system

Each subject was imaged using a passive markerless 3D motion capture system (DI4D Pro; Dimensional Imaging Ltd, Hillington, Glasgow, UK). Prior to capture, the system was calibrated according to the manufacturer's instructions. The procedure for capture has been described in detail elsewhere[13]. In summary, each subject practiced the rest position and maximum smile expression until the researcher was happy they had fully understood the facial expression they would need to perform. Following this, the volunteers were imaged at 60 3D images per second, performing the desired facial expression from rest to maximum smile. Each capture sequence was approximately 3 seconds in duration. The captured sequence and appropriate calibration file were imported into the specialized software DIHydra, which generated approximately 180 individual 3D images. These were saved for post-capture processing.

Post-capture processing

For each subject, the first frame of the sequence was imported into DI3DView software. Using the alignment function, the initial image was reorientated so that the x-plane (axial plane) passed through the inter-canthal line and was parallel to the Frankfort plane, the y-plane (sagittal plane) passed through the mid inter-canthal point at nasion, and the z-plane (coronal plane) passed through the bilateral tragal points. The image was adjusted manually until both operators (BSK and CJL) agreed that the orientation was correct (Fig. 1). The reorientated 3D image was then saved.

The transformation matrix used to re-orientate the initial image was used to reorientate all of the remaining images in the sequence into the new co-ordinate system. The initial image was landmarked with 22 landmarks (Table 1) and the same landmarks were tracked through the entire image sequence using the automatic tracking function within the software. The accuracy of the automatic landmark tracking algorithm has been validated previously and found to be clinically acceptable[14]. To account for head movement, the forehead landmarks (1 to 4) were used for image stabilization, while the remaining 18 landmarks were used in the analysis. Finally, the tracked landmark data (x, y, and z-coordinates) were exported in .PC2 file format and converted into a format readable by Microsoft Excel using in-house software.

Analysis

Asymmetry score based on clinically derived midline

The 3D co-ordinate configuration (original configuration) for each frame was imported into MATLAB from the Microsoft Excel file. First, the centroid (geometric centre) of the 18-landmark configuration was computed. Second, the 3D configuration was scaled to a common centroid size. Finally, a 'reflected' landmark configuration was produced by reflecting the re-scaled original landmark configuration around the sagittal plane, which represented the 'clinically derived midline'. An

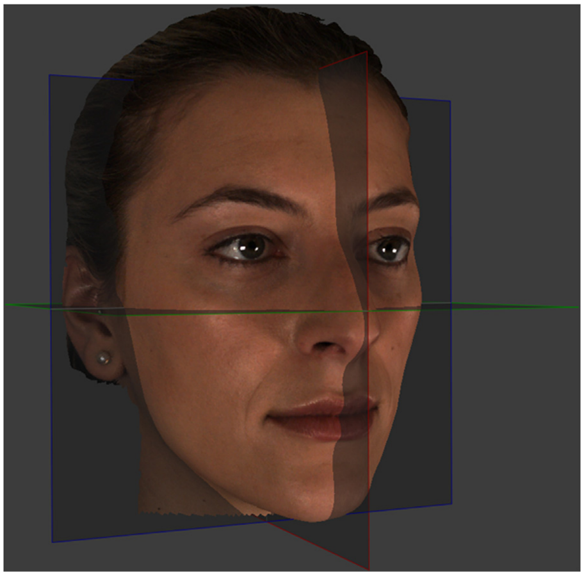

Fig. 1. Reorientated image showing the *x*-plane (axial plane – green) parallel to the intercanthal line and parallel to the Frankfort plane; *y*-plane (sagittal plane – red) perpendicular to the axial plane passing through nasion; *z*-plane (coronal plane – blue) passing through the bilateral tragal points perpendiicular to the axial plane.

'individual midline configuration' was created by calculating the mean of the original configuration and its reflected version. The Euclidean distances between each of the pairs of landmarks, i.e. the original landmark and the individualized midline, were calculated. The facial asymmetry score was calculated as follows: the Euclidean distances between landmark pairs were squared and summed, then divided by the total number of landmarks ($n = 18$) in the analysis. This procedure was repeated for each of the 3D images in the subject's 3D capture sequence from rest to maximum smile.

Higher facial asymmetry scores indicate greater disparity between the landmark pairs and so a greater degree of facial asymmetry. A score of zero would represent a perfectly symmetrical face. A facial asymmetry score was produced for each individual frame from rest to maximum smile. The facial asymmetry score was recorded at three time points: rest (T_0), median time point (T_1), and maximum smile (T_2). The median time point was defined as the middle frame of the sequence from rest to maximum smile.

Asymmetry score based on Procrustes alignment

As described previously, the 3D facial landmark configuration (original configuration) was imported into MATLAB. New code was written to align the 3D configurations using generalized Procrustes analysis instead of using the clinically derived midline. As before, this involved computing the centroid for each 3D configuration and scaling the configuration to a common centroid size. However, this time the original landmark configuration was reflected around an arbitrary plane, translating and rotating the reflected 3D configuration over the original configuration to achieve 'best-fit'. Best-fit was achieved when the sum of the squared distances between the original landmark configuration and its reflected 3D configuration was minimal. For each frame, an 'individual midline configuration' was created by calculating the mean of the original configuration and its reflected version, and the facial asymmetry score was calculated[8]. In addition to the facial asymmetry score based on the 18 landmark pairs, a decomposed lip asymmetry score based on the 10 lip landmarks alone was calculated[15]. This method allows facial features, i.e. the lips, which have different numbers of landmarks, to be compared on the same scale.

Table 1. Landmark definitions.

Number	Name	Landmark definition
1–4	Stabilization points	Points placed in each corner of the forehead, used as stable points to eliminate head movement
5	Right cheilion	Point located at the right labial commissure
11	Left cheilion	Point located at the left labial commissure
6		Point located on the vermilion border midway between right cheilion and right crista philtre
10		Point located on the vermilion border midway between left cheilion and left crista philtre
7	Right crista philtre	Point on the right crest of the philtrum, located just above the vermilion border
9	Left crista philtre	Point on the left crest of the philtrum, located just above the vermilion border
13	Labrale inferius	Point indicating the lower border of the lower lip
12		Point midway between right cheilion and labrale inferius
14		Point midway between left cheilion and labrale inferius
15	Right subalare	Point on the margin of the base of the right ala where it disappears into the skin of the upper lip
16	Left subalare	Point on the margin of the base of the left ala where it disappears into the skin of the upper lip
17	Right exocanthion	Point on the outer commissure of the right eye fissure
20	Left exocanthion	Point on the outer commissure of the left eye fissure
18	Right endocanthion	Point on the inner commissure of the right eye fissure
19	Left endocanthion	Point on the inner commissure of the left eye fissure
21	Nasion	Point in the midline of both the nasal root and the nasofrontal suture, always above the line that connects the two inner canthi
22	Pronasale	Point on the tip of the nose
8	Labrale superius	Point indicating the midpoint of the upper vermilion border

Error study

The error of the method was determined by taking the facial capture sequences of 12 volunteers at random and repeating the alignment and landmarking procedures as described previously. The landmarking error was not assessed in isolation, as there would be additional error associated with image reorientation. There was a period of over 4 weeks between the first and second reorientation and landmark digitizations to avoid memory bias. The difference in magnitude of the asymmetry scores between the two digitizations was assessed, as well as the random and systematic error.

Results

Error study

The difference in magnitude of the asymmetry score for the face and lips between the two digitizations was less than 0.1 (Table 2). Systematic error was assessed by paired *t*-test and random error was assessed by coefficient of reliability. No systematic errors were observed and all coefficients of reliability were above 90%.

Asymmetry score based on clinically derived midline

Gender differences

As assessed by two-sample *t*-test, there was no statistically significant difference between the female and male facial asymmetry scores at rest ($P = 0.363$), median time point ($P = 0.559$), or at maximum smile ($P = 0.888$). For the lips, male subjects presented a statistically significant higher lip asymmetry score than female subjects ($P = 0.043$) at the median time point; however the difference in asymmetry score was only 0.18. There was no significant difference in asymmetry scores at rest ($P = 0.217$) or at maximum smile ($P = 0.284$). As these differences were not clinically significant, the results for male and female subjects were combined for further analysis.

Temporal differences

A one-way repeated measures analysis of variance (ANOVA) with Bonferroni adjustment was used to determine whether there were any statistically significant differences between the facial asymmetry scores at rest, median time point, and maximum smile. The facial asymmetry score at rest (0.76) was significantly lower than the score at the median time point (0.93) and maximum expression (0.98). In addition, there was as a significant difference between the median time point (0.93) and maximum expression (0.98). This was also the case for the lips; at rest (0.93), at the median time point (1.34), and at maximum expression (1.45) (Table 3). None of the mean differences or 95% confidence intervals for the facial or lip asymmetry scores between the three time points was greater than 0.5.

Asymmetry score based on Procrustes alignment

Gender differences

As assessed by two-sample *t*-test, there was a statistically significant difference between the female and male facial asymmetry scores at rest ($P = 0.041$), median time point ($P = 0.001$), and at maximum smile ($P = 0.008$). This would not be clinically significant, as none of the mean differences or 95% confidence intervals for the facial or lip asymmetry scores reached the threshold value of 0.5 derived following the pilot study. In all cases, male subjects had higher scores than female subjects. For the lips, there was a statistically significant difference in asymmetry scores between male and female subjects at the median time point ($P = 0.002$) and at maximum smile ($P = 0.007$); there was no difference at rest ($P = 0.064$). Again the differences were subclinical and the results for male and female subjects were combined for further analysis.

Temporal differences

One-way repeated measures ANOVA with Bonferroni adjustment showed a significantly lower facial asymmetry score at rest (0.81) than at the median time point

Table 2. Error study—the difference in magnitude of the asymmetry score for the face and lips.

	Rest (T_0)		Median time point (T_1)		Maximum smile (T_2)	
	Face	Lips	Face	Lips	Face	Lips
Asymmetry score	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Based on clinically derived midline	0.1 ± 0.2	−0.1 ± 0.4	0.1 ± 0.2	−0.1 ± 0.3	0.1 ± 0.2	0.0 ± 0.4
Based on Procrustes alignment	0.0 ± 0.1	0.3 ± 0.2	0.0 ± 0.1	−0.1 ± 0.1	0.0 ± 0.1	−0.1 ± 0.2

SD, standard deviation.

Table 3. Differences in asymmetry score based on the clinically derived midline, between mean female and male values and combined values at rest, median, and maximum frames for the face and lips during smiling.

	Rest (T_0)			Median time point (T_1)			Maximum smile (T_2)		
	Mean ± SD	95% CI		Mean ± SD	95% CI		Mean ± SD	95% CI	
		Lower	Upper		Lower	Upper		Lower	Upper
Face									
Female	0.77 ± 0.20	0.72	0.83	0.91 ± 0.22	0.87	0.85	0.98 ± 0.26	0.91	1.05
Male	0.76 ± 0.19	0.71	0.81	0.94 ± 0.27	0.87	1.01	0.99 ± 0.33	0.90	1.07
Combined	0.76 ± 0.20	0.73	0.80	0.93 ± 0.24	0.88	0.97	0.98 ± 0.29	0.93	1.04
Lips									
Female	0.90 ± 0.28	0.83	0.98	1.25 ± 0.37	1.15	1.35	1.40 ± 0.48	1.27	1.53
Male	0.97 ± 0.26	0.90	1.04	1.43 ± 0.52	1.57	1.29	1.50 ± 0.48	1.37	1.63
Combined	0.93 ± 0.27	0.88	0.99	1.34 ± 0.46	1.25	1.43	1.45 ± 0.48	1.36	1.54

CI, confidence interval; SD, standard deviation.

(0.99) and at maximum smile (1.02). There was no significant difference between the median time point and maximum smile. For the lips, there were statistically significant differences in asymmetry scores at rest (1.05), median time point (1.42), and at maximum smile (1.50) (Table 4). None of the mean differences or 95% confidence intervals for the facial or lip asymmetry scores between the three time points was greater than 0.5.

Discussion

It is widely accepted that facial asymmetry is an undesirable characteristic that has a negative impact on the individual's quality of life[3]. Currently, quantifying the degree of facial asymmetry is based on static 2D or 3D images. This method of assessment, based on two time points, is unable to capture the dynamic nature of the smile. The present study used a validated and clinically acceptable imaging modality, passive 3D motion markerless stereophotogrammetry, to capture dynamic facial motion. The system was set to capture the smile at 60 3D frames per second at the correct fidelity. The inclusion criteria, based on assessment of the 3D images and examination of the volunteers, contributed to a 'normal' homogeneous sample of female and male adult subjects. The authors acknowledge the cost and expertise involved in the routine capture of facial dynamics using this technology, but such methods could be beneficial to objectively quantify the complex dynamic nature of facial motion following surgical and non-surgical interventions. For example, monitoring the resolution of Bell's palsy, post-stroke rehabilitation, or following facial nerve grafting. Previous studies based on clinical anthropometric measurements and on static 3D images have reported a baseline level of asymmetry, at rest, in clinically symmetrical faces between individuals[8,16–22]. A statistical difference in asymmetry score, at rest, between the genders was not found in the present study, which is in agreement with previously published data[8,17,20,23].

This study also found no clinical difference in facial and lip asymmetry scores between male and female subjects half way through the smile (median time point) or at maximum smile. Direct comparison of the results with those of previous studies is not possible as the outcome measures vary between studies. Published outcome measures include asymmetry based on shell-to-shell deviations (root-mean-square distances) between the original and mirrored facial meshes of individuals[17–20]. This method may yield incorrect results as the deviations are based on distances between two nearest points on a surface rather than corresponding points[24]. In addition, the use of Euclidean distance matrix analysis (EDMA) to quantify changes in shape has also been reported[23]. Other studies have used landmark analysis and morphometric outcomes to present an 'asymmetry index'[22]. The only study that used a similar method of analysis and asymmetry score found very similar asymmetry scores at rest (0.80) and at maximum smile (0.91)[8]. This previous study was a 3D study and assessed the facial asymmetry score based on 27 landmarks.

A novel finding of the present study was that facial asymmetry increased over the duration of the smile in a non-linear fashion. This would suggest that with minimal oral facial musculature activity, faces at rest are at their most symmetrical. From rest to median smile, individuals have greater scope to smile asymmetrically as there are minimal anatomical constraints. At the extremes of the smile, the muscle bundle length, orientation, and overlying fascia may begin to restrict this ability. This could result in a non-linear increase in asymmetry over time. Hallac et al. reported the mean asymmetry score from rest to maximum smile based on a small number of controls[9]. Using the mean asymmetry score over the entire duration of the smile may over- or under-estimate the asymmetry score depending on the individual scores or outliers for each frame between rest and maximum smile. The present study used a specific, well defined third time point (median frame) between rest and maximum smile for each individual to overcome this problem. Even though there was a statistically significant increase in smile asymmetry over the duration of the smile, it would not be clinically significant. This is as expected, based on the inclusion criteria.

Procrustes superimposition and the clinically derived midline produced similar asymmetry scores at the three time points. This would be expected, as both methods scale the 3D landmark configuration to a common centroid size. Using Procrustes superimposition, the original and reflected configurations are translated to a common centroid position and then rotated to minimize the distances between the landmarks for 'best fit'. Whilst using the clinically derived midline, the landmarks are reflected following rescaling. For symmetrical faces, there would be minimal differences between Procrustes superimposition and the clinically derived midline technique. Interestingly, the Procrustes-based asymmetry scores were slightly larger than those based on the clinically derived midline. During Procrustes superimposition, all landmarks will move as the 3D configuration reorientates and so the distances between landmark pairs will all increase (unless there is absolutely no asymmetry). On the other hand, landmarks in the midline, using the clinically derived

Table 4. Differences in asymmetry score based on Procrustes alignment, between mean female and male values and combined values at rest, median, and maximum frames for the face and lips during smiling.

	Rest (T_0)			Median time point (T_1)			Maximum smile (T_2)		
	Mean ± SD	95% CI		Mean ± SD	95% CI		Mean ± SD	95% CI	
		Lower	Upper		Lower	Upper		Lower	Upper
Face									
Female	0.78 ± 0.19	0.73	0.83	0.91 ± 0.23	0.85	0.97	0.94 ± 0.22	0.88	1.00
Male	0.85 ± 0.19	0.80	0.90	1.06 ± 0.24	1.00	1.13	1.10 ± 0.37	1.00	1.20
Combined	0.81 ± 0.19	0.78	0.85	0.99 ± 0.25	0.94	1.03	1.02 ± 0.31	0.96	1.08
Lips									
Female	1.00 ± 0.28	0.92	1.07	1.31 ± 0.37	1.21	1.41	1.39 ± 0.37	1.29	1.48
Male	1.09 ± 0.26	1.03	1.16	1.54 ± 0.39	1.43	1.64	1.59 ± 0.40	1.48	1.69
Combined	1.05 ± 0.27	0.99	1.10	1.42 ± 0.39	1.35	1.50	1.49 ± 0.40	1.41	1.56

CI, confidence interval; SD, standard deviation.

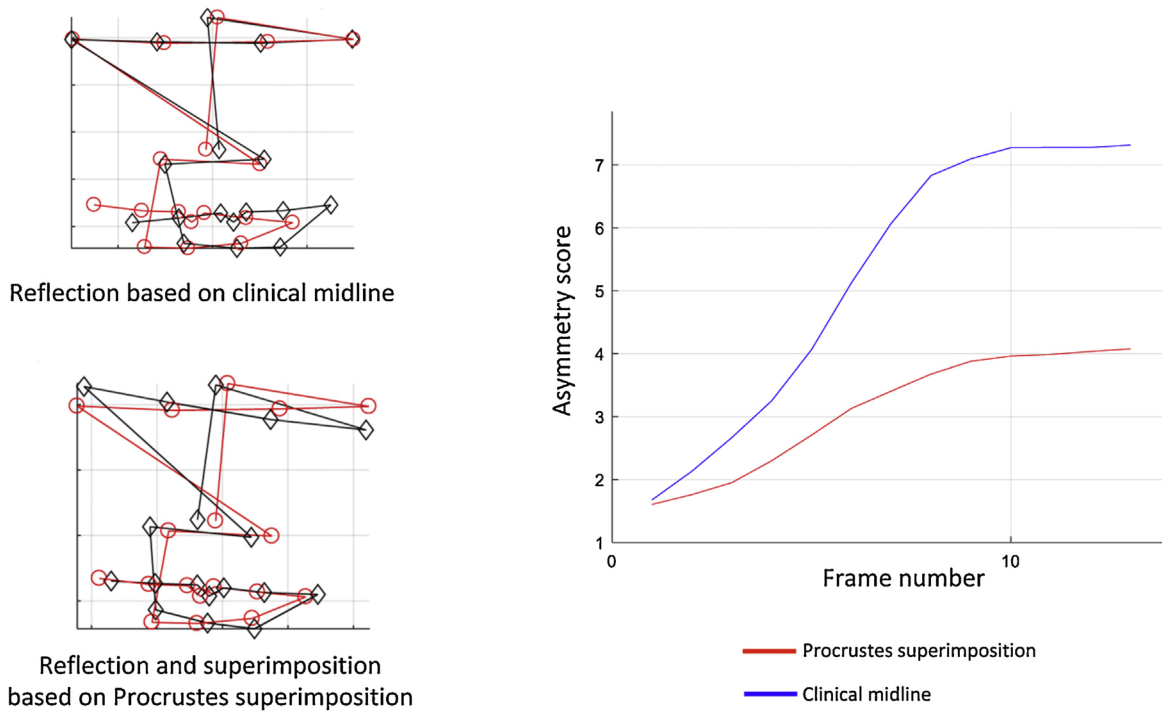

Fig. 2. Asymmetry scores based on the clinically derived midline and on Procrustes superimposition.

midline, will not move and so will reduce the mean score by contributing in number but not in magnitude.

This is not the case for asymmetrical faces. In the example of an individual presenting with Bell's palsy affecting the left side of the face, the asymmetry scores are greater when using the clinically derived midline than when using Procrustes superimposition (Fig. 2). The facial asymmetry score was smaller because Procrustes superimposition will reorientate the entire 3D facial landmark configuration to minimise the distance between corresponding landmarks i.e. for 'best fit'. Clinically this would be equivalent to the patient smiling asymmetrically, but changing the orientation of their head to minimize their smile asymmetry. Even though the smile is asymmetric, the displacement of the landmarks around the upper face and eyes during the Procrustes superimposition contribute to the overall global asymmetry score

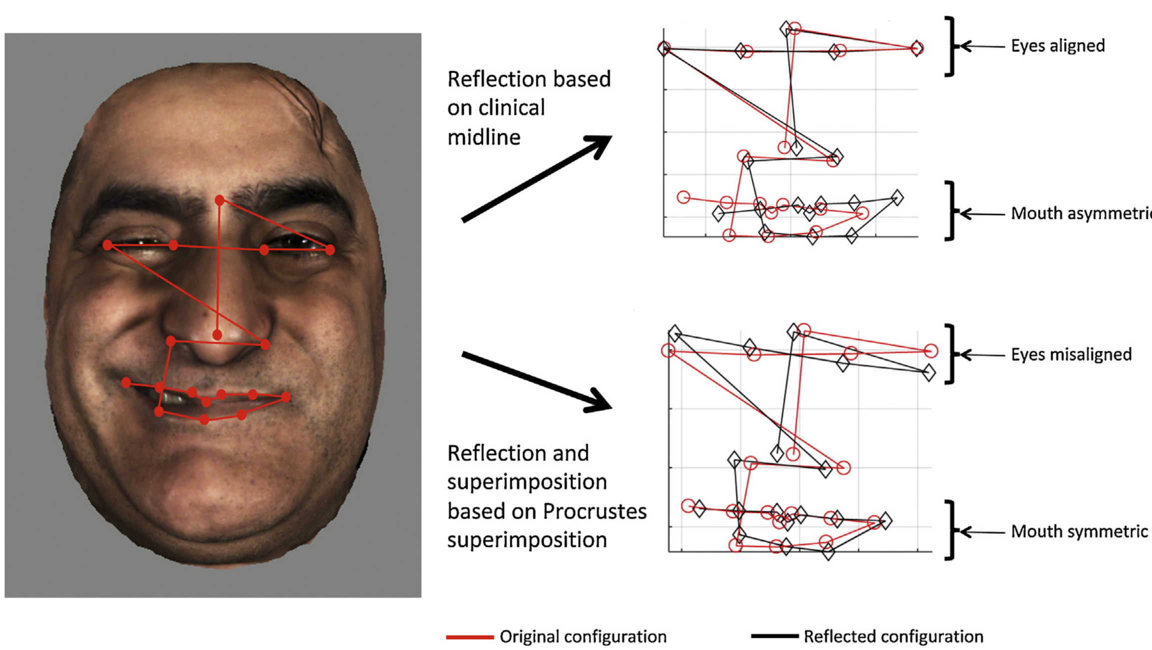

Fig. 3. In an individual with an asymmetric smile, the displacement of the landmarks around the upper face and eyes during the Procrustes superimposition contributes to the overall global asymmetry score.

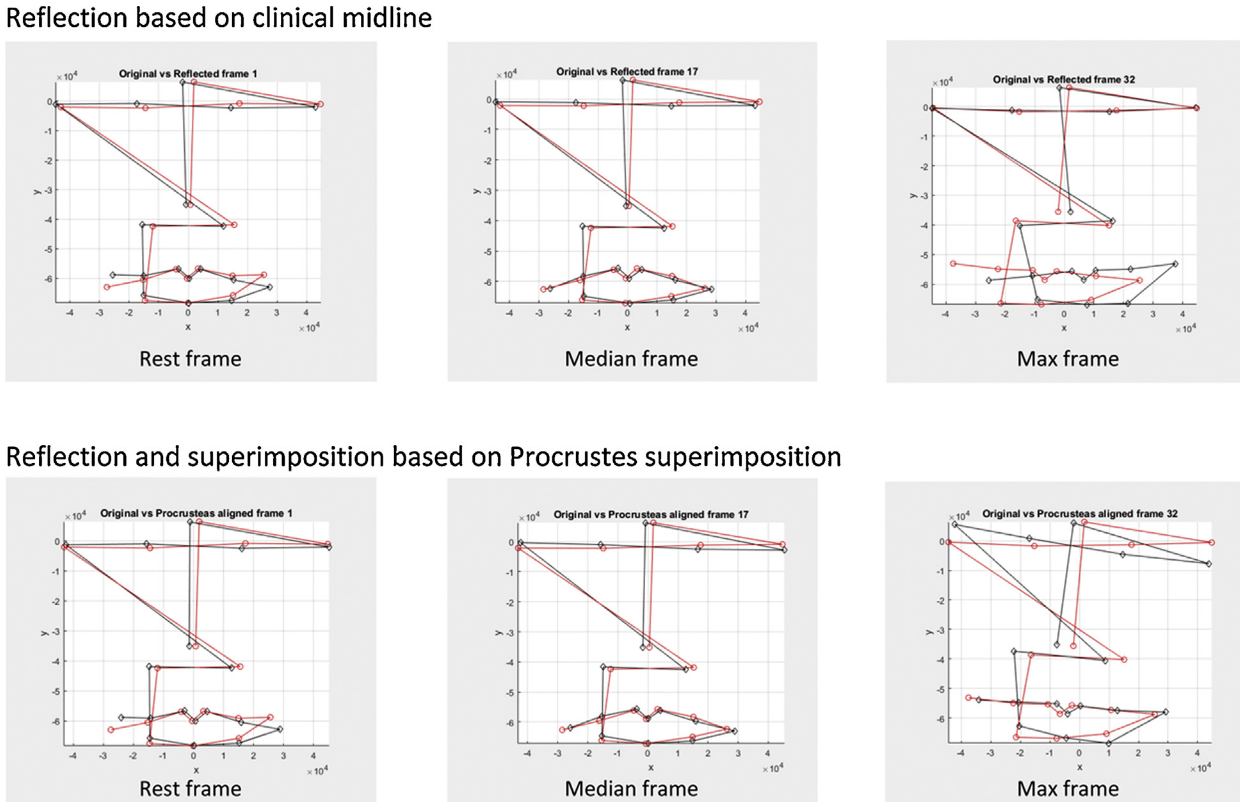

Fig. 4. Using the clinically derived midline, the upper face remains static and the true asymmetry of the smile is seen over the expression of the smile. Using Procrustes superimposition, the face changes in orientation during smiling, which is not clinically valid.

(Fig. 3). Procrustes superimposition is integral in Procrustes analysis, which compares the shape of two objects, for example human skull shapes[25]. This method of superimposition works well on static objects. However applying the same technique to a dynamic series of objects, i.e. a non-symmetric smiling face, forces the 'best fit' component of the algorithm to override the need to maintain the orientation of the facial image. In other words, shape differences are determined but at the cost of reducing the clinical validity of the outcome. This situation does not occur clinically, and a more clinically valid representation is obtained using the clinically derived midline, where the upper face remains static and the true asymmetry of the smile is seen over the expression of the smile (Fig. 4). The use of a clinically derived midline may be controversial, but a previous study found that 'direct manual placement' of geometric vertical midlines on facial images was rated the best method of determining the midline over automated methods[10].

In conclusion, fluctuating facial asymmetry exists within individuals, as well as between individuals. The difference in facial and lip asymmetry scores between male and female individuals is probably subclinical. Throughout a smile, facial and lip asymmetry scores increase over the duration of the expression, from rest to maximum smile. Procrustes superimposition and the clinically derived midline produced similar asymmetry scores and both are valid for symmetrical faces. However with facial asymmetry, Procrustes superimposition may not be a valid measure and the use of a clinically derived midline may be more appropriate. A novel baseline dataset of dynamic facial and lip asymmetry scores has been presented, which could be used as a yardstick to compare the outcomes of facial surgery or emotion where facial function may be affected.

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None.

Competing interests

None.

Ethical approval

Ethical approval was obtained from the Dental Research Ethics Committee (DREC) at the University of Leeds, UK (DREC reference 240915/BK/179).

Patient consent

Patient consent was obtained to publish the clinical photographs.

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