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ABSTRACT

The aim of this study was to use 3D motion facial capture technology to quantify the fluctuating dynamic facial asymmetry, during smiling, in a group of "normal" adults. 54 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. Based on either a clinically derived midline or on Procrustes alignment a facial asymmetry score was calculated; based on the Euclidian distance between landmark pairs. Facial asymmetry scores were determined at three-time point; rest, median and maximum frame. Based on both the clinically derived midline and on Procrustes alignment, the differences between males and females, and at the three different time points were not clinically significant. However throughout a smile, facial and lip asymmetry scores increase over the duration of the smile. Fluctuating facial asymmetry exists within individuals, as well as between individuals. The use of Procrustes superimposition or a clinically derived midline produces similar asymmetry scores and is 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 but this requires further investigation.

INTRODUCTION

Facial attractiveness and beauty are important underling 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 minimise facial asymmetry and to correct any clinically significant facial asymmetry respectively. As well as assessing pan-facial symmetry, the symmetry of specific facial regions have been reported, for instance the nasio-labial 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. rest and at maximum smile[8]. The study found a statistically significantly 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 partly been addressed in a comparative study of a small group of non-cleft controls (n=11) with repaired unilateral cleft lip and palate patients (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 provide some limited information, they either fail to capture the true dynamic nature of smiling or present limited data.

The development of 3D motion capture technology has allowed capture of non-verbal expressions from rest to maximum expression. To assess reflective symmetry, the left and right sides of the face need to reflected or mirrored around a mid-facial plane. The mid-facial plane can be clinically determined based on anatomical landmarks, or mathematically derived[10]. The later 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 is to use 3D motion facial capture technology to quantify the fluctuating dynamic facial asymmetry between a group of clinically "normal" Caucasian adult males and females. The null hypothesis states that there is no difference in the magnitude of overall facial asymmetry, based on the asymmetry score, between genders. In addition, the effects of using a clinically or mathematically derived midline will be investigated.

MATERIALS AND METHODS

Sample size calculation

A pilot study was undertaken to determine the asymmetry scores of a group of 7 volunteers with a clinically significant asymmetric smile (assessed by BSK and CL), and 7 individuals with a clinically symmetrical smile. The difference in asymmetry scores of 0.5 determined the threshold of clinical significance. This together with the standard deviation of the differences (0.7), power of 0.8 and statistical difference of (0.0035), following a Bonferroni correction for multiple testing, resulted in a sample size of a minimum of 43 individuals per group.

Subjects

Following ethical approval from the Dental Research Ethics Committee (DREC) at the University of Leeds, U.K. (DREC reference 240915/BK/179), 54 male and 54 female volunteers were recruited to take part in the study. Volunteers were recruited if they meet the following inclusion criteria: they were between the ages of 18 and 40 years, no previous facial surgery, no lip piercing, no history of facial trauma or neurological facial problems. In addition subjects recruited were clinically symmetrical and had class I incisors as judged by one experienced Consultant NHS Orthodontist and an orthodontic trainee.

Imaging using DI4D™ Pro passive stereophotogrammetric capture system

Each subject was imaged using a passive markerless 3D motion capture system (DI4D, Dimensional Imaging, Hillington, Glasgow). Prior to capture, the system was calibrated according to the manufacturer's instructions. The procedure for capture has been described elsewhere in detail[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 patients 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 specialised software DIHydra, which generated approximately 180 individual 3D images, which 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 re-orientated so 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 CL) agreed the orientation was correct, Figure 1. The re-oriented 3D image was then saved. The transformation matrix used to re-orientate the initial image was used to re-orientate 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 previously been validated and was found to be clinically acceptable[14]. To account for head movement, the forehead landmarks (1 to 4) were used for image stabilisation, 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. Firstly, the centroid (geometric centre) of the 18 landmark configuration was computed. Secondly, 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 "individual midline configuration" was created by calculating the mean of the original configuration and its reflected version. The Euclidian distances between each of the pairs of landmarks, i.e. the original landmark and the individualised midline, were calculated. The facial asymmetry score was calculated as follows; the Euclidian distance 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.

The higher the facial asymmetry score, the greater the disparity between the landmark pairs and so the greater the 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 previously described, the 3D facial landmark configuration (original configuration) was imported into MATLAB. New code was written to align the 3D configurations using generalised 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 were 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.

Error study

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

RESULTS

Error study

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

Asymmetry score based on clinically derived midline

Gender differences

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

Temporal differences

A one-way repeated measures analysis of variance (ANOVA) with a Bonferroni adjustment was used to determine whether there are any statistically significant differences between the facial asymmetry scores at rest, median time point and maximum smile. There was a significantly lower facial asymmetry score at rest (0.76) compared to 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 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 were greater than 0.5.

Asymmetry score based on Procrustes alignment

Gender differences

Following a two-sample *t*-test there were statistical 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% confident limit intervals for the facial or lip asymmetry scores reached the threshold value of 0.5 derived following the pilot study. In all cases males had higher scores than females. For the lips, there was a statistical difference in asymmetry scores between males and females 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 sub-clinical and the results for males and females were combined for further analysis.

Temporal differences

A one-way repeated measures analysis of variance (ANOVA) with a Bonferroni adjustment showed a significantly lower facial asymmetry score at rest (0.81) than at the median time point (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 statistical differences in asymmetry score 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 were greater than 0.5.

DISCUSSION

It is widely accepted that facial asymmetry is an undesirable characteristic that has a negative impact on the quality of life of an individual[3]. Currently, quantifying the degree of facial asymmetry is based on static two-dimensional or three-dimensional images. This method of assessment, based on two time points, is unable to capture the dynamic nature of the smile. The present study uses 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" homogenous sample of female and male adult patients. 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 intervention. 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[8,16,17,18,19,20,21,22]. A statistical difference in asymmetry score, at rest, between genders was not found in the present study, which was in agreement with previously published data[8,17,20,23].

The present study also found no clinical difference in facial and lip asymmetry scores between males and females half way through the smile (median time point) and maximum smile. Direct comparison of the results with 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[17,18,19,20]. 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 which uses 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 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 increases 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 facia may begin to restrict this ability. This could result in a non-linear increase in asymmetry over time. Hallac et al., (2015) 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 uses 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 would be as expected based on the inclusion criteria.

The asymmetry scores at the three time points based on the clinical midline, and on Procrustes superimposition, were similar. 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, then rotated to minimise the distances between the landmarks for "best fit". Using the clinically derived midline, the landmarks are reflected following rescaling. For symmetrical faces there would be minimal translation and rotation during Procrustes superimposition, as the centroids for the original and reflected landmark configurations would be identical in size and similar in location; hence the small differences between the asymmetry scores compared to 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 the landmarks will move as the 3D configuration re-orientates and so the distance between landmark pairs will all increase (unless there is absolutely no asymmetry). On the other hand, landmarks in the midline, using the clinically derived 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 this 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 using Procrustes superimposition, Figure 2. For the global facial asymmetry score, the differences are less marked because the landmark configuration following Procrustes superimposition will re-orientate the entire 3D facial landmark configuration for "best fit". Clinically this would be equivalent to the patient smiling asymmetrically, but changing the orientation of their head to minimise their smile asymmetry. Even though the smile is asymmetric, the displacement of the landmarks around the upper face and eyes during the Procrustes superimposition are contributing to the overall global asymmetry score, Figure 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 over-ride the need to maintain the orientation of the facial image. In other words shape differences are determined but at the cost of reducing the clinically 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, Figure 4. The use of a clinically derived midline may be controversial but a previous study has shown that "direct manual placement" of geometric vertical midlines on facial images was rated as 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 between facial and lip asymmetry scores between males and females is probably subclinical. Throughout a smile, facial and lip asymmetry scores increase over the duration of the expression, from rest to maximum smile. The use of Procrustes superimposition or a clinically derived midline produces similar asymmetry scores and is 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 data set of dynamic facial and lip asymmetry scores has been presented, which can be used as a yard-stick to compare the outcome of facial surgery or emotion where facial function may be affected.

Declarations

Funding: None

Competing Interests: None

Ethical Approval: Ethical approval from the Dental Research Ethics Committee (DREC) at the University of Leeds, U.K. (DREC reference 240915/BK/179).

Patient Consent: Patient consent has been obtained to publish clinical photographs

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Table 1 Landmark definitions

Number	Name	Landmark definition
1 - 4	Stabilisation 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 christa philtre.
10		Point located on the vermilion border midway between left cheilion and left christa philtre.
7	Right christa philtre	Point on the right crest of the philtrum, located just above the vermilion border.
9	Left christa 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 the 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.

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	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Asymmetry score 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
Asymmetry score 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

Table 3 Descriptive statistics showing the differences in asymmetry score, based on clinically derived midline, between females, males 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 Lower	95% CI Upper	Mean	SD	95% CI Lower	95% CI Upper	Mean	SD	95% CI Lower	95% CI Upper
Face												
Females	0.77	0.20	0.72	0.83	0.91	0.22	0.87	0.85	0.98	0.26	0.91	1.05
Males	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												
Females	0.90	0.28	0.83	0.98	1.25	0.37	1.15	1.35	1.40	0.48	1.27	1.53
Males	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

Table 4 Descriptive statistics showing the differences in asymmetry score, based on Procrustes alignment, between females, males 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												
Females	0.78	0.19	0.73	0.83	0.91	0.23	0.85	0.97	0.94	0.22	0.88	1.00
Males	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												
Females	1.00	0.28	0.92	1.07	1.31	0.37	1.21	1.41	1.39	0.37	1.29	1.48
Males	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

Figure legends

Figure 1 Re-orientated image x-plane (axial plane - green) passed through the inter-canthal line and parallel to the Frankfort plane, the y-plane (sagittal plane - red) passing through the mid inter-canthal point at nasion, and the z-plane (coronal plane - blue) passing through the bilateral tragal points.

Figure 2 Asymmetry scores based the clinically derived midline than using Procrustes superimposition.

Figure 3 In an asymmetric, the displacement of the landmarks around the upper face and eyes during the Procrustes superimposition are contributing to the overall global asymmetry score.

Figure 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 valid clinically.