Quantitative Facial Asymmetry: Using Three-Dimensional Photogrammetry to Measure Baseline Facial Surface Symmetry

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Background: Although symmetry is hailed as a fundamental goal of aesthetic and reconstructive surgery, our tools for measuring this outcome have been limited and subjective. With the advent of three-dimensional photogrammetry, surface geometry can be captured, manipulated, and measured quantitatively. Until now, few normative data existed with regard to facial surface symmetry. Here, we present a method for reproducibly calculating overall facial symmetry and present normative data on 100 subjects.

Methods: We enrolled 100 volunteers who underwent three-dimensional photogrammetry of their faces in repose. We collected demographic data on age, sex, and race and subjectively scored facial symmetry. We calculated the root mean square deviation (RMSD) between the native and reflected faces, reflecting about a plane of maximum symmetry. We analyzed the interobserver reliability of the subjective assessment of facial asymmetry and the quantitative measurements and compared the subjective and objective values. We also classified areas of greatest asymmetry as localized to the upper, middle, or lower facial thirds. This cluster of normative data was compared with a group of patients with subtle but increasing amounts of facial asymmetry.

Results: We imaged 100 subjects by three-dimensional photogrammetry. There was a poor interobserver correlation between subjective assessments of asymmetry ($r = 0.56$). There was a high interobserver reliability for quantitative measurements of facial symmetry RMSD calculations ($r = 0.91–0.95$). The mean RMSD for this normative population was found to be 0.80 ± 0.24 mm. Areas of greatest asymmetry were distributed as follows: 10% upper facial third, 49% central facial third, and 41% lower facial third. Precise measurement permitted discrimination of subtle facial asymmetry within this normative group and distinguished norms from patients with subtle facial asymmetry, with placement of RMSDs along an asymmetry ruler.

Conclusions: Facial surface symmetry, which is poorly assessed subjectively, can be easily and reproducibly measured using three-dimensional photogrammetry. The RMSD for facial asymmetry of healthy volunteers clusters at approximately 0.80 ± 0.24 mm. Patients with facial asymmetry due to a pathologic process can be differentiated from normative facial asymmetry based on their RMSDs.

Clinical Question/Level of Evidence: Diagnostic, II.

Key Words: Facial symmetry, asymmetry, photogrammetry, facial analysis, anthropometry, three-dimensional, Procrustes, RMSD

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Facial symmetry has been correlated with attractiveness[1–4] and is one of the fundamental goals of both reconstructive and aesthetic facial plastic surgery.[5,6] A certain amount of asymmetry is inherent to any face[7] and is tolerated by an observer as within normal limits.

Beyond a threshold level of asymmetry however, facial features become dysmorphic. Historically, we have relied on time-consuming and limited direct patient measurement (direct anthropometry) to quantitate facial features.[7] Today, with the advent of three-dimensional photogrammetry imaging systems, we can perform an infinite number of quantitative facial measurements on static archived images (indirect anthropometry).[8] Whereas traditional techniques have allowed only for the measurements of distances or angles,[9] we are now able to compare surface features of the face in a three-dimensional manner with high degrees of accuracy and resolution.[10,11] Innovative three-dimensional imaging technology is rapidly becoming part of the routine evaluation of patients with facial differences, yet few normative data exist with which to compare these results.

We demonstrate a method for reproducibly and rapidly calculating a single number value for facial surface symmetry with a plane of maximum symmetry from three-dimensional photogrammetry. Using this calculation, we quantitatively examined facial asymmetry in a cohort of 100 volunteers to delineate the normative distribution for facial asymmetry present in the population at large. When compared with this distribution, patients with facial asymmetry secondary to underlying pathology were found to be outliers and could be distinguised based on this single numeric root mean square deviation (RMSD) value.

MATERIALS AND METHODS

After institutional review board approval was obtained, we recruited 100 volunteers to participate in this study. Patients with a history of facial trauma, facial operations, or craniofacial diagnoses were excluded. We obtained demographic data including age, sex, and race. Surface scans of subjects' faces were obtained using the Canfield Vectra stereo photogrammetry system[12] (Canfield Imaging Systems, Fairfield, NJ) with the volunteer in repose.

These 100 images of faces in repose, without manipulation, were scored by 2 observers for subjective asymmetry using a scoring system of 1 = mild asymmetry, 2 = moderate asymmetry, and 3 = severe asymmetry. To test interobserver reliability, we calculated a Pearson correlation coefficient for interobserver reliability using STATA SE 10 Statistical Software (StataCorp, College Station, TX) for this subjective assessment of facial asymmetry.

We calculated quantitative facial asymmetry from these same 100 images. The face, including the forehead, the midface, and the chin, were manually selected for manipulation, but the ears, the hairline, and the neck were excluded. Initially, we manually attempted to position a sagittal plane to divide the right and left hemifaces. This was found to be subjective and irreproducible. Instead, a plane of maximum symmetry was generated by maximizing the fit of the native and reflected images, which is equivalent to minimizing the RMSD between the 2 surfaces (Fig. 1) using the Procrustes technique.[13–15] Root mean square deviation is defined by the following equation:

$$x_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_N^2}{N}}.$$

The face was reflected about this unique calculated plane of maximum symmetry, and the RMSD between the native and reflected surfaces was calculated. This translates to averaging the distances between the 2 surfaces to give us a single number in millimeters for the mean differences between the native and reflected faces. Thirty images were chosen to test interobserver reliability. Three independent observers analyzed these 30 images, and descriptive statistics were calculated. To test interobserver reliability, we calculated a Pearson correlation coefficient for interobserver reliability using STATA SE 10 Statistical Software (StataCorp).

After demonstrating interobserver reliability, the data set of 100 volunteers was similarly analyzed, and individual RMSD values were calculated. In addition, we noted which facial third (upper, middle, or lower) demonstrated the greatest area of asymmetry. Facial thirds were defined according to the 3-section Canon using the trichion, nasion, subnasale, and gnathion. We then used Excel (Microsoft, Redmond, WA) to calculate mean and median values for RMSDs for this normative group as well as the standard deviations.

To compare our subjective and objective assessments of facial asymmetry in this normative group, we converted the contiguous

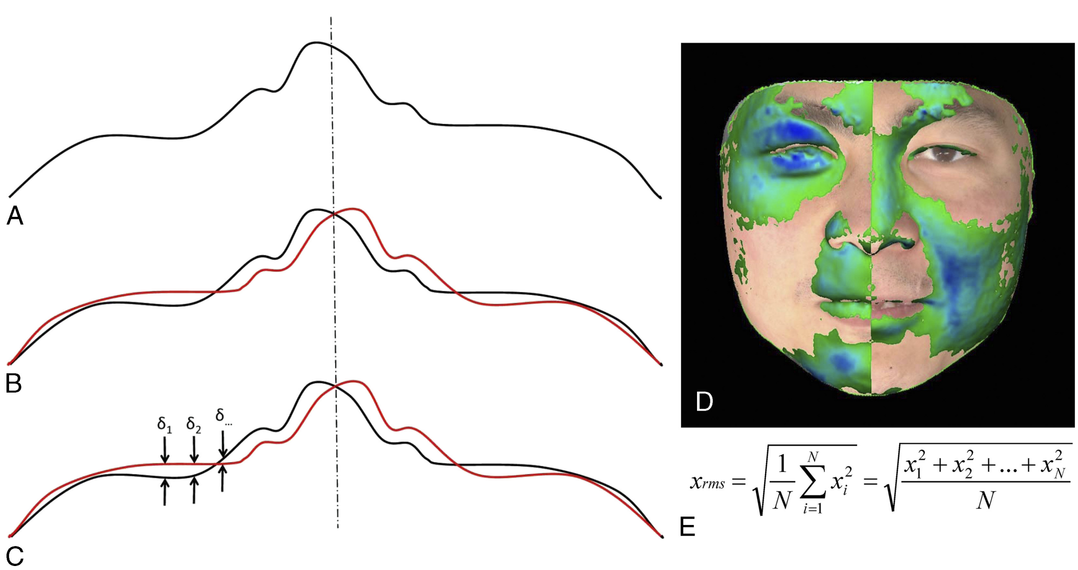

FIGURE 1. Explanation of symmetry calculations. Images of normative faces in repose were captured, and their facial surfaces were isolated for analysis. Rather than relying on a manually determined plane for rotation, a unique plane of maximum symmetry was determined by minimizing the RMSD between the native surface shown descriptively in black (a) and its reflection shown in red (b). By minimizing the differences between the 2 surfaces or maximizing the fit (c), a unique plane of maximum symmetry is determined. The facial surface is then reflected with this unique plane, and the differences between the native and reflected surfaces are calculated (d) according the equation for RMSD (e).

TABLE 1. Demographics of 100 Normative Volunteers

Characteristic	N = 100
Age, mean, y	34.2
Range	1–84
Male-female	52:48
Ratio	1.08
Asian	11
Black	10
White	71
Hispanic	5
Other/mixed	2
Native American	1

variable of RMSD to a categorical variable using the same system of 1 (RMSD, 0.42–0.84 mm), 2 (RMSD, 0.84–1.26 mm), and 3 (RMSD, 1.26–168 mm). A Pearson correlation coefficient between these subjective and objective scores was calculated using STATA SE 10 Statistical Software (StataCorp) for each of the 2 observers' scores and the objectively measured RMSDs.

Finally, for comparison with our normative group, we calculated the RMSDs for 3 patients with subjectively increasing facial asymmetry due to hemifacial microsomia, progressive facial hemiatrophy, and fibrous dysplasia.

RESULTS

We obtained high-quality photogrammetry images from 100 volunteers without underlying craniofacial diagnoses or trauma. Demographic data for volunteer subjects are shown in Table 1. Subjective assessment by the 2 independent observers failed to demonstrate significant correlation, using a scoring system of mild, moderate, and severe asymmetry (r = 0.56), suggesting poor agreement as to what constituted mild, moderate, or severe asymmetry.

By computationally calculating a plane of maximum symmetry and measuring the RMSD, the interobserver reliability for measured facial asymmetry was excellent (r = 0.91 between observers 1 and 2, 0.95 between observers 2 and 3, and 0.93 between observers 1 and 3) (Fig. 2). The distribution of facial asymmetry as calculated by RMSD is shown in Figure 3. The mean and median RMSDs of this normative group were 0.80 and 0.77 mm, respectively. The SD of this distribution was calculated as 0.24 mm. Facial asymmetry was maximal in the upper facial third of 10%, in the midface of 49%, and the lower face of 41% of the subjects.

Just as there was a poor agreement between the observers as to subjective facial asymmetry in this normative group, so too was there a poor correlation between the subjective and objective scores (r = 0.276 for observer 1 and r = 0.39 for observer 2).

Comparison of the RMSDs of patients with subtle but known pathology was distinguishable from those of the population of norms, with RMSDs greater than 1.0 mm, and RMSD increasing as expected with subjective amounts of facial asymmetry. Their images and relative RMSDs are shown in Figure 4.

DISCUSSION

Three-dimensional photogrammetry has become a routine part of patient evaluation in orthodontics, oral surgery, and plastic surgery. Although the technology has been rapidly adopted because of its ability to capture surface anatomy with ease and speed and without radiation, remarkably few data exist on its utility and baseline values. Several pilot studies have demonstrated that photogrammetry can be used reliably for indirect anthropometry.[8,16–18] Photogrammetry is particularly useful in performing indirect anthropometry in young children, who may not be able to cooperate with direct measurements. Although photogrammetry used to this end may broaden the subject base for facial measurements, it does not significantly expand our capabilities beyond the rule and caliper. We sought to take full advantage of this technology to measure surface anatomy, rotate it in space, and calculate surface symmetry. This allows us to easily measure an elusive variable in plastic surgery, surface symmetry.

We confirmed our impression that facial asymmetry is poorly assessed subjectively. Two independent observers failed to agree as

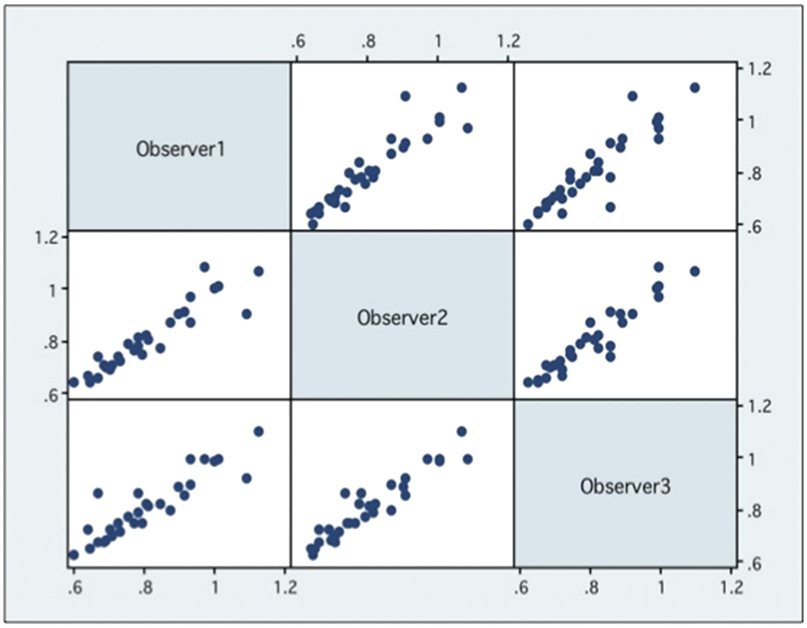

FIGURE 2. Interobserver reliability for 3 independent observers on 30 normative images using Pearson correlation coefficients for paired comparison. With the use of the unique plane of maximum symmetry for RMSD calculations, this was found to be excellent with an r = 0.91 between observers 1 and 2, 0.95 between observers 2 and 3, and 0.93 between observers 1 and 3.

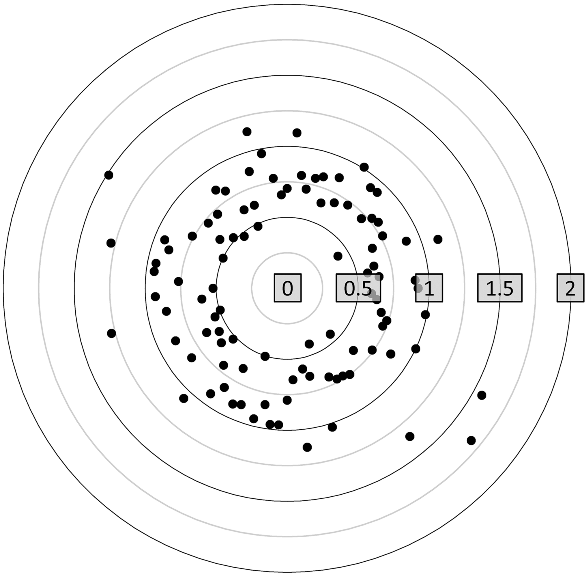

FIGURE 3. The distribution of facial asymmetry RMSD values plotted in polar coordinates for 100 normative subjects. The center of the bull's-eye represents an RMSD of 0 or perfect symmetry, with increasing RMSD values designated in millimeters expanding from this nadir. The mean and median RMSDs of this normative group were 0.80 and 0.77 mm, respectively. The SD of this distribution was calculated as 0.24 mm.

to whether subjects had mild, moderate, or severe asymmetry by independent assessment of the three-dimensional images. Both observers had most subjects scored as moderate asymmetry, which perhaps acted as a "catchall" bin for those cases that were difficult to assess.

Our initial attempts at quantitatively measuring surface symmetry were performed using manual placement of a plane of symmetry bisecting the face. It became readily apparent that human error and variability outweighed the actual amount of asymmetry, masking the signal with the noise of manual positioning. Where to position this plane of symmetry was subjective, and the results were not reproducible, even when we tried to follow consistent anthropometric landmarks (eg, nasion, subnasal, gnathion). Small variations in the position of this plane with which reflection was performed resulted in large differences between the native and reflected faces. In addition, craniofacial scoliosis often resulted in landmarks that did not fall along a single plane.[19] Others have also noted that the use of a selection of landmarks for identifying a plane of symmetry is unreliable.[20] We abandoned this approach and instead focused on mathematically defining the plane of maximum symmetry, theoretically a unique plane, absent of operator error. By minimizing the RMSDs between the native and reflected faces, this unique plane of maximum symmetry could be identified, and an RMSD for any face could be reproducibly calculated. This is analogous to the Procrustes technique used by others for similar measurements.[13,14,21,22]

The consistency of surface symmetry measurements was confirmed by a near linear correlation among calculations performed on a subset of 30 faces by 3 independent observers (Fig. 2). This plane of maximum symmetry is not defined by anthropometric landmarks, which demonstrate individual variability, and may lie off a single plane if there is facial curvature. Instead, this unique plane is identified by maximizing the fit (which is equivalent to minimizing the RMSD) between the native and reflected facial surfaces. The small discrepancies in the RMSD values generated by different observers reflect small deviations in the surface area selected for measurement.

More subjects had the area of greatest asymmetry in the midface (49%) or lower face (41%), whereas only 10% of subjects demonstrated greatest asymmetry in the upper face. This may reflect the more complex architecture of the midface and the lower face when compared with the forehead. Alternatively, it may reflect the greater degree of animation in the midface and the lower face when compared with the relatively static upper face. We imaged subjects in repose, but the relative degree of animation is one limitation to this technique of measurement.

Investigators have used a variety of techniques to measure facial symmetry including facial casts,[14,23–26] laser scans,[27–30] cephalometry,[19] and computed tomography.[31] The benefits of photogrammetry over these techniques include the ease and speed of image acquisition as well as the lack of radiation. Several authors have used three-dimensional photogrammetry in the craniofacial patient population to assess symmetry and the effects of surgery and molding.[14,20,22,32–36] Yet, few data exist on normative facial asymmetry with which to compare our craniofacial patients and benchmark our surgical results. Our population of 100 norms demonstrates

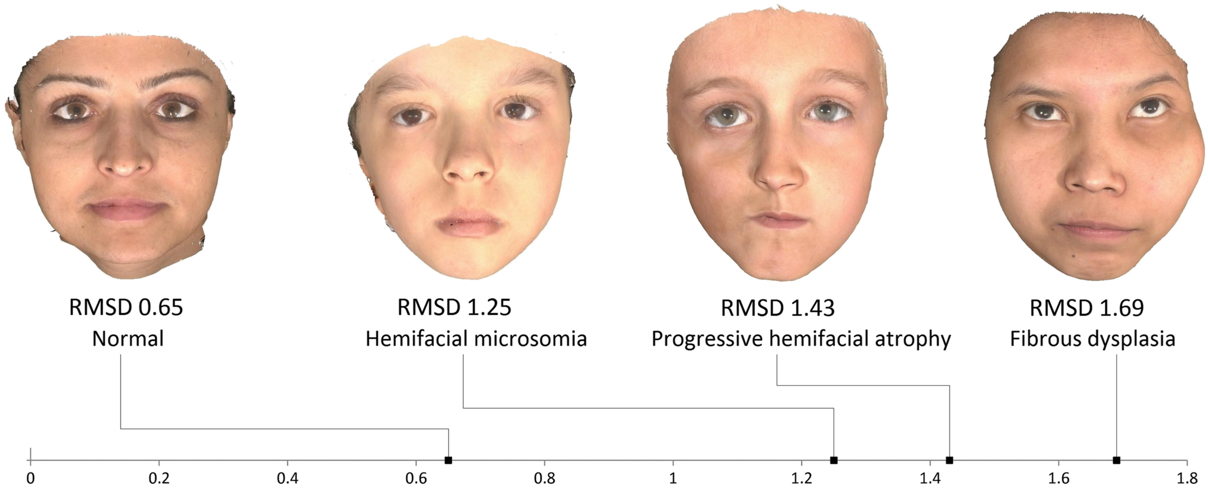

FIGURE 4. The asymmetry ruler. With the use of the RMSD values (in millimeters), even subtle facial asymmetry can be quantitatively distinguished from our normative population. Here, a subject within the normative group, with an RMSD of 0.65 mm, is shown alongside patients with increasing asymmetry secondary to mild hemifacial microsomia, progressive hemifacial atrophy, and fibrous dysplasia. With the use of this technique, patients' surface facial asymmetries can be quantitatively measured and plotted on this normative ruler.

tight clustering of RMSD at approximately 0.8 mm, with an SD of 0.24 mm. Even very subtle facial asymmetry attributable to known diagnoses resulted in RMSDs that fall outside this range.

Our results for normative asymmetry are comparable with the nasal asymmetry indices found in children with repaired unilateral cleft lips who underwent presurgical nasoalveolar molding (mean, 0.74 mm), whereas children who had not undergone nasoalveolar molding had nasal RMSDs (mean, 1.2 mm) that were almost 2 SDs from our normative mean. Maull et al[14] calculated these values for the nose only, whereas our RMSD values are for the full face and would be expected to be slightly higher as a result. Ferrario et al[37] used digitized anthropometric landmarks to measure facial symmetry and concluded that 2-mm differences between the 2 hemifaces were considered within the normative range. Our calculations of full-surface symmetry suggest that there is a slightly greater symmetry, on the order of 1-mm differences.

Why is an analysis of symmetry useful? Every plastic surgeon will at some point see a patient who complains that his or her face is asymmetric, and while this may or may not be clinically evident, the severity of the asymmetry may be hard to quantitate. We demonstrated here that what may be considered mild asymmetry by one observer may be classified as moderate or severe asymmetry by another. Three-dimensional photogrammetry allows us to follow Sir Harold Gillies' wise advice, "first diagnose, then treat." A quantitative assessment of asymmetry allows us to assess the severity of the problem and place it within or outside the range of normative symmetry that we have defined here. In addition, we can follow a patient's progress along this ruler with surgical intervention.

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