Method for quantifying facial asymmetry in three dimensions using stereophotogrammetry

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The goal of orthodontic and surgical treatment of patients who have craniofacial anomalies is a harmonious facial appearance. One aspect of this appearance is facial asymmetry. Because facial asymmetry is, to a minor degree, common in most people,[1-5] the aim of surgically creating a perfectly symmetrical face is not realistic, nor is it even desirable. To make an objective distinction between minor and major asymmetry, it is advisable to quantify facial asymmetry. Quantification makes it possible to demonstrate the amount of facial asymmetry for diagnostic purposes, observe development of facial asymmetry during growth, and evaluate treatment results.

The selected location of the reference plane is an important factor in the quantification of asymmetry in objects that are nearly symmetrical bilaterally, such as the human head. Within a three-dimensional coordinate system, a reference plane can be defined, first, by three midsagittal anatomical landmarks, or second, by one pair of bilateral anatomical landmarks with an additional constructed landmark centered between these two bilateral landmarks. The last option allows for construction of a plane perpendicular to the line that connects the bilateral landmarks through the additional landmark. Using these guidelines, many researchers[2,3, 6-9] have introduced lines which represent reference planes that can be used to study asymmetry in two-dimensional pictures. These studies demonstrate a preference for defining reference planes by means of landmarks related to the eyes. The arguments for using the eyes are that they are a natural frame of reference used by everyone in everyday life,

Abstract

A three-dimensional method to quantify facial asymmetry is introduced. Stereophotogrammetry was applied to determine three-dimensional (3-D) coordinates for eight pairs of surface landmarks of 106 individuals, including 16 with an operated complete unilateral cleft lip and palate. Facial asymmetry was quantified from four different reference planes that were defined perpendicular to and bisecting lines between pairs of bilateral landmarks related to the eyes, nose and mouth. Significant differences ($P<0.01$) between these four planes were determined using multivariate analyses of variance (MANOVA). It is concluded that the best reference plane to select in studies of facial asymmetry is formed by the one which is perpendicular to and bisects the line that connects the landmarks Exocanthion. Reproducibility and validity of the method is demonstrated.

Key Words

Facial asymmetry • Three-dimensional • Reference plane • Stereophotogrammetry.

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Table 1
Number of subjects (N), mean age in months with standard deviation (sd) of the total Comparison and the total UCLP group and divided by sex.

	Comparison group		UCLP group	
		Age		Age
	N	mean ± sd	N	mean ± sd
total	80	110.3 ± 16.9	16	86.6 ± 18.1
male	44	113.3 ± 15.7	11	89.5 ± 9.6
female	36	106.4 ± 17.6	5	80.2 ± 20.1

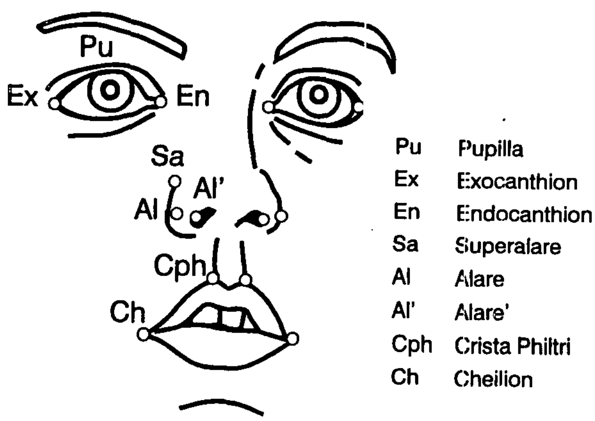

Figure 1

Figure 1
Schematic picture of a face including the 8 pairs of bilateral landmarks used.

and the main development in this part of the face occurs in the early years.

Because facial asymmetry can be resolved in the transverse, vertical and sagittal directions, a three-dimensional registration method is essential to observe these components simultaneously. Stereophotogrammetry makes it possible to calculate distances and angles within a three-dimensional coordinate system.[10] Since this method is noninvasive, it is suitable for studying facial asymmetry in children.

The objectives of the present study were: to present a three-dimensional method to quantify facial asymmetry; to compare reference planes defined by anatomical landmarks related to the eyes, nose, and mouth; and to determine which planes can be used accurately in analyses of facial asymmetry.

Materials and methods

The material consisted of 90 individuals without craniofacial anomalies (comparison group, N=80; reproducibility group, N=10) and 16 patients with an operated complete unilateral cleft lip and palate (UCLP group). No selection was made regarding facial morphology/asymmetry. Table 1 shows the age and sex distribution for the comparison group, which was drawn from patients who visited the Academic Centre for Dentistry Amsterdam (ACTA) for general dental treatment, or for the UCLP group, which comprised patients treated by the cleft lip and palate team of the University Hospital Dijkzigt/Sophia in Rotterdam. Using stereophotogrammetry, three-dimensional (3-D) coordinates were determined for eight pairs of surface landmarks that were clearly recognizable and have been described by other authors.[1,11-13] The landmarks selected are shown in Figure 1.

Stereophotogrammetry is a three-dimensional registration method. Two photographs (transparencies) that were taken with two semi-metric cameras (Rollei® 6006 Réseau) form a stereopair (Figure 2). With the use of an analytical plotter (Kern® DSR11) and a stereopair, it is possible to reconstruct a three-dimensional image of the object. Three-dimensional coordinates can be calculated for anatomical landmarks that are identified semi-automatically on the 3-D image.

The method developed to quantify asymmetry is based on the following mathematical principle: If a reference plane and two points (P and Q) are defined in space (Figure 3A), it will be possible to move the points in such a way (P′ and Q′) that a symmetrical arrangement to the reference plane can be created (Figure 3B). Many movements can be carried out to obtain such a result. However, the points have to be moved for a particular minimal movement that represents the asymmetry of the original configuration. This minimal movement can be determined by constructing an additional point (P′) that is symmetrical with point Q (Figure 3C), and calculating the distance between point P and the additional point P′ (Figure 3D). This distance in millimeters is a measure for the amount of asymmetry, and is called D_{total}.

A reference plane can be positioned between a pair of bilateral landmarks while it is defined perpendicular in all directions to the line through these landmarks (Figure 4). In this way, four reference planes were defined by the

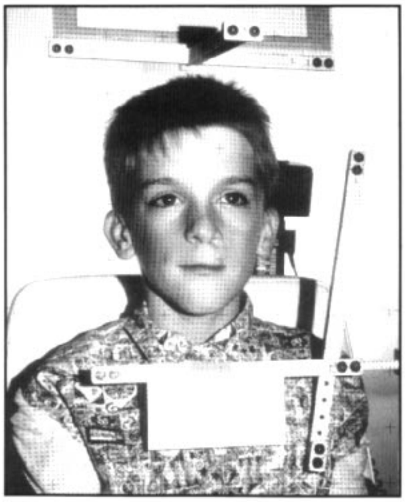

Figure 2A

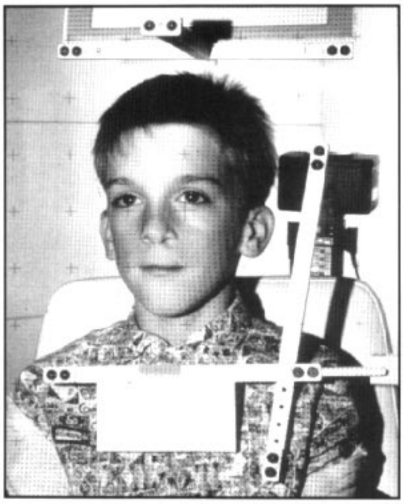

Figure 2B

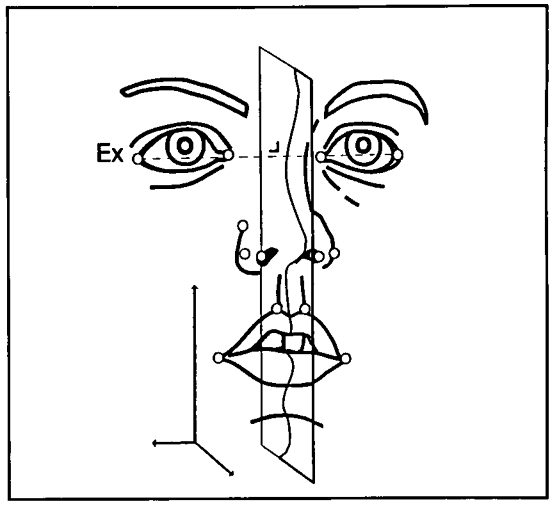

Figure 4

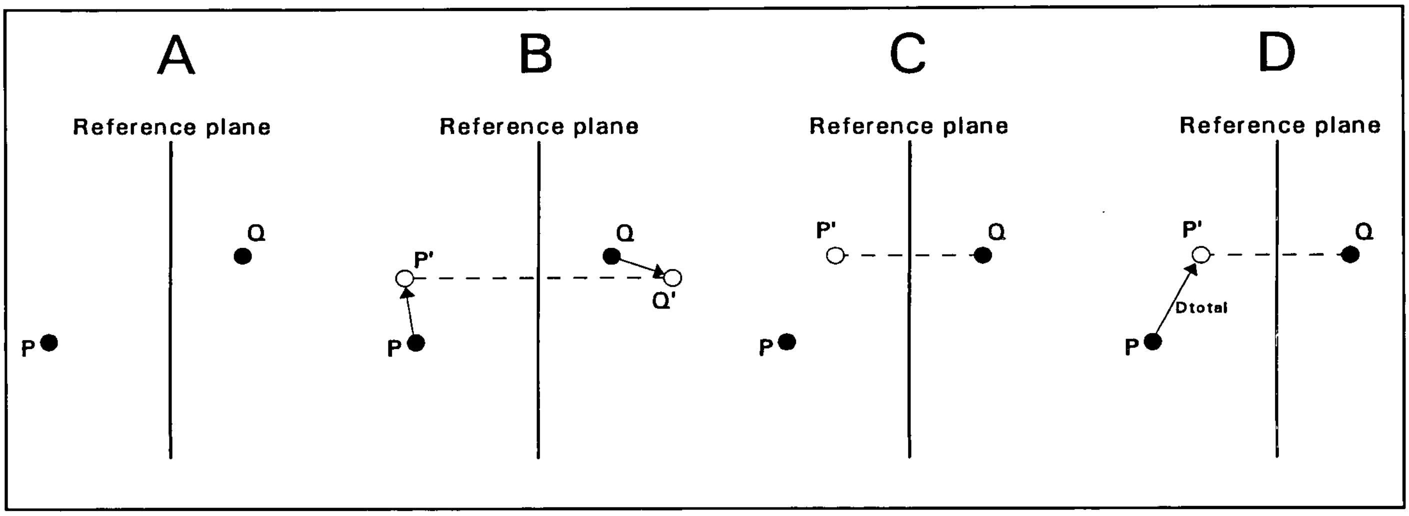

Figure 3

bilateral landmarks Exocanthion (plane A), Endocanthion (plane B), Superalare (plane C), and Cheilion (plane D). The smallest distances between the landmarks to the defined planes were determined, as well as the smallest angles between the lines which connect bilateral landmarks with the defined planes. These data were used for calculating D_{total} of the bilateral landmarks for the comparison group. To identify facial asymmetry in three dimensions, the best reference plane to select would be the plane with the lowest D_{total}. The four planes were compared by means of multivariate analyses of variance (MANOVA; $P<0.01$) of the SPSS® software package.

Reproducibility

To determine the reproducibility of the method, two sets (T1 and T2) of stereopairs were taken from the reproducibility group with an interval of about 48 hours. Three-dimensional coordinates for the selected land-

Figure 2A-B
An example of a stereopair of a patient having an operated complete unilateral cleft lip and palate.

Figure 3
A: Two-dimensional picture of a three-dimensional representation with a reference plane orientated perpendicular to the plane of the picture and two point P and Q, representing a pair of bilateral landmarks.
B: To create a symmetrical arrangement of the point P and Q with the reference plane, it is possible to move, for example, point P to P' and point Q to Q'.
C: To determine the minimal movement needed to create a symmetrical arrangement, an additional point P' is constructed in such a way that it is symmetrical with point Q.
D: The distance in millimeters (D_{total}) over which point P has to be moved to point P' to create a symmetrical arrangement of the bilateral landmarks P and Q is a measure for the amount of asymmetry of the original configuration.

Figure 4
Schematic picture of a face including reference plane A which is positioned between the bilateral landmarks Exocanthion, while it is defined perpendicular in all directions to the line through these landmarks.

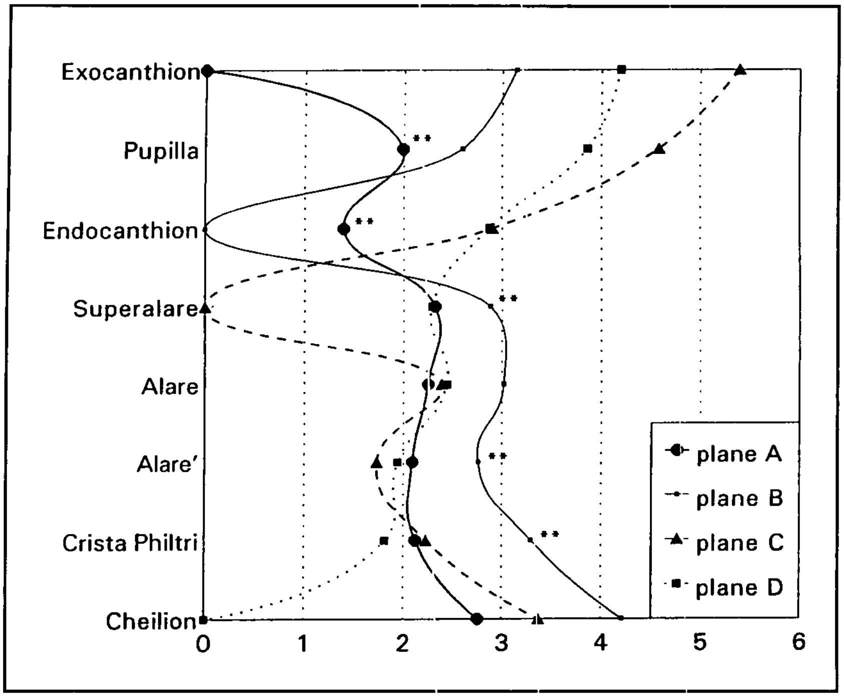

Figure 5

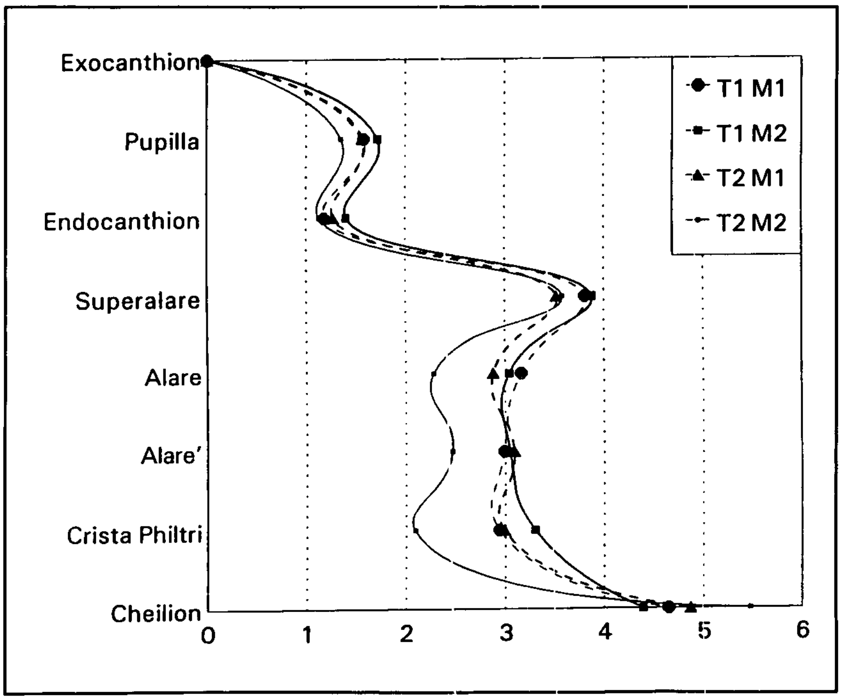

Figure 6

Figure 5
Mean D_{total} (mm) of the bilateral landmarks, from cranial to caudal, for planes A, B, C and D. ** shows significant differences (P<0.01) in comparison with the other planes.

Figure 6
Mean D_{total} (mm) of the bilateral landmarks, from cranial to caudal, for the different recordings (T1, T2) and the repeated measurements (M1, M2). No significant differences (P>0.02) can be demonstrated between the different recordings and the repeated measurements.

marks were determined twice (M1, M2) on both stereopairs by the same operator. D_{total} of the relevant landmarks for plane A were calculated. Repeated measurements (M1 and M2) of a single recording give an indication of the measuring error. Differences between measurements of the first (T1) and second (T2) recording give an indication of the posing error including the measuring error. To ascertain differences between the different recordings, as well as between repeated measurements, a MANOVA was carried out with D_{total} as dependent variables and repeated measurement and recording as within-subject factors.

Usually a test is carried out to reject the null hypothesis. If this rejection is done while the null hypothesis is true, the mistake will be called a type I error. However, in this case, the test was carried out for the purpose of rejecting the alternative hypothesis. A type II error will then constitute if the null hypothesis is rejected wrongly. It is customary to set an upper limit of 20% (P<0.2) for the risk of making a type II error.

Validity

D_{total} of the relevant landmarks for plane A were calculated for the UCLP group. The expectation was that if the method was valid, the UCLP group would show higher asymmetry scores within the region of the cleft anomaly in comparison with the comparison group. Significant differences between the UCLP and the comparison group were determined with the use of a MANOVA with D_{total} as a dependent variable and group and landmark as within-subject factors. Because of differences in age distribution between the groups (Table 1), the variable age was entered as covariate.

Results

Figure 5 shows the mean D_{total} of the bilateral surface landmarks for the planes A, B, C, and D. The bilateral landmarks that define the reference planes show, as expected, a D_{total} of zero. Significant differences between the planes are given (MANOVA, F=36.37; df=27,53; P<0.01). Compared with planes A, C, and D, plane B shows significantly higher D_{total} for the landmarks Superalare, Alare' and Crista Philtri. Other than the landmarks that define the planes in the region of the nose and mouth, there are no significant differences for the D_{total} between the planes A, C, and D. In the region related to the eyes, plane A shows a significantly lower D_{total} for the landmarks Pupilla and Endocanthion compared with the other planes. These results demonstrate that plane A generally shows the lowest D_{total} for the landmarks in the regions related to the eyes, nose, and mouth. Therefore, it is concluded that plane A is the best reference plane to select in studies of facial asymmetry.

Reproducibility

Figure 6 shows the mean D_{total} of repeated measurements (M1, M2) of stereopairs from different recordings (T1, T2) for the bilateral landmarks for plane A. No main or interaction effects for repeated measurement and recording were determined (MANOVA effect recording, F=6.41; df=7,3; P>0.2; MANOVA effect measurement, F=0.66; df=7,3; P>0.2; MANOVA effect recording by measurement, F=0.87; df=7,3; P>0.2). From this, it is concluded that this method to quantify facial asymmetry is reproducible.

Validity

Figure 7 shows, for the comparison and the UCLP groups, the mean D_{total} of the bilateral landmarks for plane A. Additionally, significant differences between the two groups are presented (MANOVA, F=2.18; df=17,77; P<0.01). The subjects with an operated complete unilateral cleft lip and palate showed, as expected, significantly more asymmetry in the region related to the cleft anomaly compared to subjects without craniofacial anomalies. Age did not influence this outcome significantly (P>0.05). In this way, the validity of the method to quantify facial asymmetry introduced here has been demonstrated.

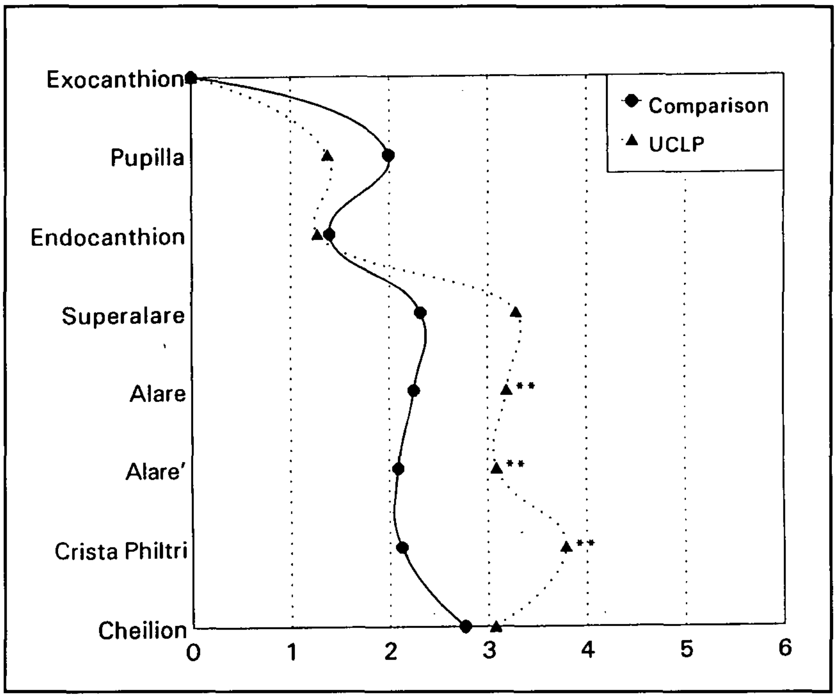

Figure 7

Figure 7
Mean D_{total} (mm) with standard deviation (sd) of the bilateral landmarks, from cranial to caudal, for comparison and UCLP groups.

**** shows significant differences (P<0.01) in comparison with the comparison group.**

Discussion

Facial asymmetry has been studied both qualitatively and quantitatively using photographs and radiographs. Qualitative assessments[14-16] are subjective, because asymmetry is judged by a selected panel, and usually is based on a two-dimensional picture of a three-dimensional object. Because of this, it is impossible to acquire an accurate picture of the sagittal component of asymmetry which is located perpendicular to the plane of the photo/radiograph. Additionally, the interpretation of facial asymmetry will be influenced by the level of standardization during the recording, because the pictures have to be taken parallel with the sagittal component of asymmetry.

Quantitative studies of facial asymmetry do not have these disadvantages, because the asymmetry has objectively been calculated. However, if two-dimensional pictures are used, the same shortcomings exist. In quantitative studies, a comparison between the right and left side is made. These methods usually determine differences between distances,[1,7,17,18] angles,[8] and surfaces or contours.[9,19,20] A disadvantage of these methods is that none of them take into account the position of the landmarks used in relation to each other. Therefore, it is possible to conclude, wrongly, that symmetry exists in an asymmetrical case.

Since asymmetry of the face occurs in all three dimensions,[21] a valid three-dimensional analysis with a registration method to match is required. In this study, stereophotogrammetry is preferred to direct measurement,[1] roentgen stereophotogrammetry,[18,22-24] magnetic resonance imaging (MRI), computer tomography (CT),[25] and laser scanning techniques[26] because it is noninvasive and the pictures give a good impression of the surface of the object. To study facial asymmetry, the following mathematical approach is useful: If an object is symmetrical, it is possible to define a plane that splits the object into two equal opposite parts. Using this principle, Wolff[4] created "normal," "left," and "right" faces. He concluded, as have others,[1-3,16] that the symmetrical face does not exist. The present study used the same mathematical approach to quantify facial asymmetry. The method is based on the fact that two landmarks can be arranged symmetrically to a plane by means of a minimal spatial movement of the landmarks (Figure 3). This minimal movement in millimeters is a measure for the amount of asymmetry of the original configuration.

The best reference plane for evaluating facial asymmetry was found in this study to be one perpendicular to and bisecting the line which connects the landmarks Exocanthion. Burke[11] criticized the use of this line. He used this line to construct a line of symmetry on a contourmap, a two-dimensional picture obtained by means of stereophotogrammetry. However, the line that connects the landmarks Exocanthion is not necessarily parallel with the plane of the picture. Thus, the line of symmetry does not represent the plane of symmetry in three dimensions. Other studies[1,3,6] have demonstrated that landmarks around the lateral border of the orbits show the least asymmetry, supporting the hypothesis that these landmarks are the most suitable landmarks to define a reference plane to study asymmetry. Obviously, these landmarks cannot be used to construct a reference plane in subjects with asymmetrical craniofacial anomalies related to the eyes.

The reproducibility of the method has been demonstrated. Measuring error and posing error did not influence the results significantly, probably because the landmarks Exocanthion are separated by a relatively large distance, reducing the effect of a slight error. In addition, the positions of these landmarks is only minimally influenced by facial muscle activity. The validity of the method has been demonstrated by means of patients with an operated complete unilateral cleft lip and palate. They show, as expected, more facial asymmetry in the region of the cleft anomaly compared with subjects without any craniofacial anomalies.

Conclusions

Two conclusions have been drawn from this study. First, the distance in millimeters of the minimal movement to attain symmetrical positiona of bilateral landmarks can be used to quantify facial asymmetry. Second, the best reference plane in three-dimensional studies of facial asymmetry is the plane perpendicular to and bisecting the line that connects the landmarks Exocanthion.

Although this distance is a reliable measure of facial asymmetry, it also has a particular direction. More information about the asymmetry can be obtained by studying this direction. Therefore, it is advisable to define a three-dimensional coordinate system related to the object and to resolve this distance for the transverse, vertical, and sagittal directions. To attain such a coordinate system, the reference plane can be used as a guide.

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