The Symmetry of Faces

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Abstract

In this paper we present an application of optical metrology and image processing to oral and maxillofacial surgery. Our goal is to support the surgeon intraoperatively during the repair of a displacement of the globe of the eye. To date, the surgeon has to evaluate his operation result solely by visual judgement. Our idea is to provide the surgeon intraoperatively with a comparison of the actual 3D position of the globe of the eye and its nominal position. The nominal position is computed based on symmetry considerations. Therefore, we have developed a method to compute the symmetry plane of faces in the presence of considerable asymmetry. We tested this method on healthy faces and on faces with a defined asymmetric region created by injection of saline solution.

1 Introduction

The zygomatic fracture associated with a malposition of the globe of the eye is one of the most frequent traumata to the facial skeleton. The aim of the treatment of these fractures is the adequate anatomical reduction in order to regain function and esthetics [1]. Both are closely related to symmetry, when the globe of the eye is concerned. However, in the clinical routine the intraoperative evaluation whether the globe has be symmetrically repositioned is dependent on the subjective estimation of the surgeon instead of objective criteria. Therefore our aim is to introduce a concept for an intraoperative support of the surgeon based on an objective assessment of symmetry.

Our basic idea is to provide an intraoperative comparison of the actual operation state and a computed nominal result. The actual state is obtained by a measurement of the patient's face taken intraoperatively with an optical 3D sensor. The position of the globe of the eye is determined with the help of contact lenses. The nominal result is computed from a preoperative measurement of the patient with the same sensor. The assumption underlying the computation of the nominal eye position is that the eyes are symmetrically positioned in the face.

This symmetrical position is the status the surgeon tries to reach. The difficulty hereby is how to evaluate whether the globes of the eyes are symmetrically positioned or not.

Our approach is to compute a symmetry plane in 3D space with respect to the whole face. Healthy human faces are not perfectly symmetric and the degree of symmetry differs individually. However, on average the deviation from perfect symmetry is not very strong. This is the result of a study by Ferrario et al. about the morphometry of the orbital region [2] and another study by Koch et al. about the symmetry of the zygomatic and the zygomatic arch [3].

Knowing the symmetry plane of the face, the mirrored 3D position of the undamaged globe defines the nominal position for the displaced globe of the eye. Any deviation of the actual position from the computed nominal position indicates that the globe is not yet correctly positioned.
Therefore one essential task in our concept is to compute the symmetry plane of the face in 3D space.
One approach is to use standardized facial landmarks. Ferrario et al. defined the plane of symmetry in 3D space with respect to four feature points in the face [4].
Another more general approach to determine the symmetry plane of 2D and 3D objects is introduced by Zabrodsky [5]. He defines the symmetry distance, as a quantifier of the minimum 'effort' required transforming a given shape into a symmetric shape. The symmetry plane is determined by minimizing the symmetry value over all possible planes.
Sun uses the extended Gaussian image of the object [6]. He measures the degree of reflectional symmetry in a plane by the correlation of the orientation histogram (the discrete version of the extended Gaussian image) with itself after reflection in the plane. In order to reduce the search space he is only checking planes near the principal axis of the object. As for a perfect symmetrical body, any plane of symmetry is perpendicular to a principal axis. Minovic also determines the symmetry plane of medical entities with respect to the principal axis [7]. In the approach of Kazhdan a measure of reflective symmetry is computed for all planes through the model's center of mass [8].
However optical sensors often do not fully acquire the whole face. So the principal axis and the centroid position of the measured data do not, generally, coincide with those of the real face. In this case a method is required that can detect the symmetry plane without the knowledge of the principal axis and the position of the center of mass.
Masuda describes a method to determine the plane of symmetry in a 2D image without any knowledge of the centroid position, which can be even applied to partially symmetric figures [9]. He uses the correlation with the rotated-reflected image for the detection of the symmetry axis in a 2D image.
In this paper we describe our approach to compute a symmetry plane of human faces in 3D space which does not require the knowledge of the centroid position and the principal axis.
We present the results obtained by applying this method to data obtained of real human faces. As a major difficulty we investigate to what extent an asymmetric part in the face affects the computation of the symmetry plane. Finally, we briefly describe how the 3D position of the pupil center can be determined from a 3D measurement.

2 Computation of the Symmetry Plane

We developed a method to compute a symmetry plane of an object, described by a triangle mesh, which is arbitrarily placed in space. The concept of this method is displayed in Figure 1.
First the triangle mesh is mirrored at an arbitrary plane. Then the original mesh and the mirrored mesh are registered. The registration is divided into two steps [10]: first a coarse registration is performed that approximately aligns the two data sets. Then, a fine registration aligns them more precisely. Based on the registered data, the symmetry plane is computed as described in section 2.2.

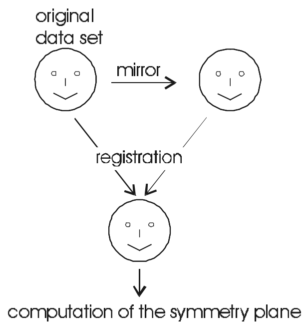

Figure 1: Scheme for finding the symmetry plane.

This method can also be applied to objects that are not perfectly symmetrical, such as e.g. human faces. The difficulties and results thereby are presented in section 3 and 4.

2.1 Fine Registration

The fine registration is based on the Iterated-Closest-Point algorithm (ICP) [11].
In a first step closest points $\mathbf{p}_i$ and $\mathbf{p}'_i$ between the two data sets are determined and afterwards a cost function depending on the distances of the closest points is minimized with respect to the six rotation and translation parameters. After applying the resulting transformation (with the rotation matrix **R** and the translation vector **t**) the algorithm starts again with the determination of (new) closest points. These steps are iterated until convergence.
Taking into account results, in [12,13], about the limits of object localization we use the following cost function:

$$\sum_i \left[c_{1i}\left(\mathbf{d}_i \cdot \mathbf{n}_i\right)\mathbf{n}_i + c_{2i}\left(\mathbf{d}_i \cdot \mathbf{e}_{1i}\right)\mathbf{e}_{1i} + c_{3i}\left(\mathbf{d}_i \cdot \mathbf{e}_{2i}\right)\mathbf{e}_{2i}\right]^2$$

$$\text{with} \qquad \mathbf{d}_i = \mathbf{p}_i - (\mathbf{R}\mathbf{p}_i^{'} + \mathbf{t})$$

$\mathbf{d}_i$ is represented in the local coordinate system of $\mathbf{p}_i$ where $\mathbf{n}_i$ is the normal direction and $\mathbf{e}_{1i}$, $\mathbf{e}_{2i}$ are the directions of minimal and maximal curvatures. c_{1i}, c_{2i} and c_{3i} are point-wise confidence values. As proposed in [13], the confidence values for the tangential directions c_{2i} and c_{3i} can be neglected against the confidence value c_{1i} for the normal direction: $c_{1i} \approx 1$, $c_{2i} \approx c_{3i} \approx 0$ [14].

2.2 Symmetry Plane

After the fine registration of the original and the mirrored mesh, the symmetry plane can be easily determined. It is given by the centers of associated points of the two data sets: each point $\mathbf{p}_i$ in the original data set is first mirrored to a point $\mathbf{p}_i$*. Afterwards the mirrored data set is registered to the original data set. Thereby each point $\mathbf{p}_i$* is transformed by a rotation matrix **R** and a translation vector **t**. The point ($\mathbf{R}\cdot \mathbf{p}_i^* + \mathbf{t}$) still corresponds to the point $\mathbf{p}_i$ and all the centers of these pairs of associated points are elements of the symmetry plane.

3 The Symmetry of Faces

We applied our method to human faces and focused our investigations on the following questions:

- Can we apply our method successfully to 'healthy' human faces?
- Can we reconstruct the symmetry plane of the former healthy face from the asymmetrical patient's face?

In the following sections we present our answers to these questions.

3.1 Data Acquisition

First of all we need a 3D measurement of the face. We use an optical sensor (Figure 2) based on phase-measuring triangulation [15,16]. Since the measurement time is short (640 ms), we can avoid motion blur.
From each camera we get a range image of the face. Afterwards, these two range images are triangulated and merged.

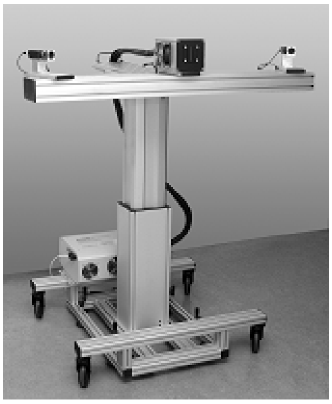

Figure 2: The phase-measuring triangulation sensor (3D-SHAPE GmbH).

3.2 Symmetry Plane in 'Healthy' Faces

As a first step we tested our method on healthy persons. We measured test persons with the optical sensor and computed the symmetry planes of their faces afterwards. For the evaluation of the symmetry plane we compared the mirrored face with the original face. If the computed symmetry plane is adequate the mirrored face should match the original one very well. However, as the face is usually not perfectly symmetrical the two data sets do not match exactly.

To evaluate the congruence of the two data sets we looked at cross sections of the overlaid data sets. One horizontal profile is depicted in Figure 3. The view shows that the mirrored data set matches the original one very well.

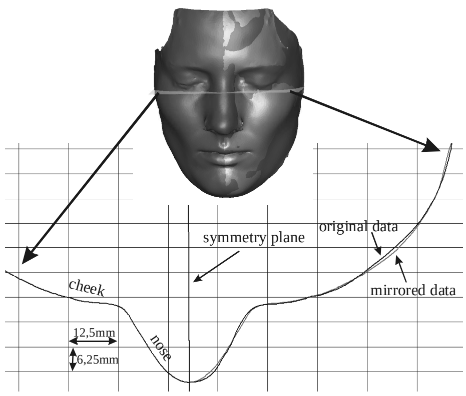

Figure 3: Comparison between the mirrored half of the face and the ‘real face’.

Moreover we evaluated quantitatively the distance of the two surfaces. The surfaces are reconstructed as triangle meshes.

For each point $\mathbf{p}_i$ of the first mesh the distance to the other mesh is computed. First of all, the closest point $\mathbf{p}'_i$ to $\mathbf{p}_i$ is determined with the help of a kD-tree [17]. Then the shortest distance from $\mathbf{p}_i$ to the triangles containing $\mathbf{p}'_i$ is calculated [18]. This distance is signed according to the orientation of the two meshes at the point $\mathbf{p}_i$.

The mean distance and the standard deviation are criteria how good the mirrored mesh matches the original mesh. In Table 1 the results for five different test persons are given.

The value of the standard deviation depends on three terms: First, the measured data is noisy. Even two overlapping data sets of the same object have a standard deviation of about 0.25 mm. Secondly, nobody is completely symmetrical. Thirdly, an incorrect symmetry plane would cause an increased standard deviation.

Another criterion for the evaluation of the symmetry plane in healthy faces is whether the mirrored position of the right globe of the eye coincides with the position of the left globe of the eye. First results are presented in section 5.

	mean distance in mm	standard deviation in mm
person 1	-0.19	1.19
person 2	0.05	0.48
person 3	0.05	0.87
person 4	0.18	0.82
person 5	-0.32	1.12

Table 1: Comparison between the mirrored data and the original data.

4 Symmetry Plane in a Patient’s Face

Now we will discuss an obvious problem: The patient’s face is asymmetrical. Therefore, we certainly cannot find a symmetry plane in this face. What we want is to reconstruct the symmetry plane, as it was when the face was intact. How can we evaluate the quality of a symmetry plane in an asymmetrical face? As we do not have the 3D data of the undamaged face, a reference is missing.

Therefore, an experiment with injections of saline solution into the malar regions of healthy test persons was performed. This study was approved by the Institutional Ethics Committee of the University of Erlangen-Nuremberg (file no. 2221). The goal was to examine to what extent asymmetric parts in the face affect the computed symmetry plane.

6 ml saline solution was injected in three steps (2 ml in each step) into the cheek of a test person. Before and after each injection the test person was measured with the optical 3D sensor. The measurements before the injections and after the third injection are displayed in Figure 4.

In the profile (Figure 4) one can see the asymmetric region generated by the injection.

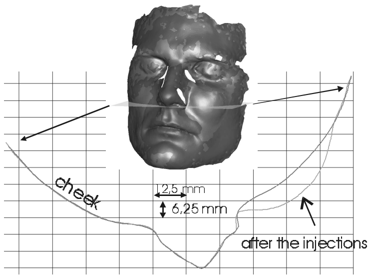

Figure 4: Before and after the injections.

The four data sets (before and after injections) have been registered so that they are all in the same coordinate system. Therefore, the computed symmetry planes can be compared.

Computing the symmetry plane of an asymmetric object, one difficulty arises: The original data set and its mirrored counterpart do not match in asymmetric regions. However, these two data sets have to be registered to compute the symmetry plane. To obtain the symmetry plane of the once intact face it is essential to take only the remaining symmetrical parts of the face into account for the registration.

One possibility to ensure this is to remove all asymmetrical parts in the original data set before it is mirrored.

Another option is to mirror the whole dataset. Then the two data sets are (manually) coarsely registered. Thereby the data sets should be aligned with respect to the symmetrical parts. For the subsequent fine registration, a distance threshold is set. Thus, only the symmetrical parts that are already well aligned are taken into account automatically.

Evaluating the experiment with the saline solution injections we have chosen the second way to register the data sets.

An example for two registered data sets is depicted in Figure 5.

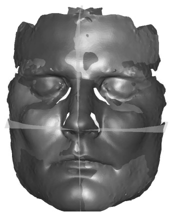

Figure 5: Original and mirrored face registered.

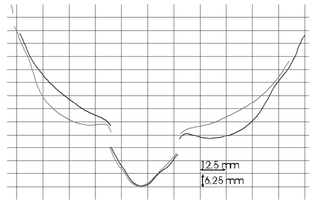

Figure 6: Horizontal cut view of Figure 5. Original face (black) and mirrored face (grey).

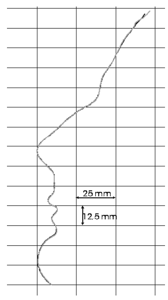

Figure 7: Cut view of Figure 5 of the side-face. Original face (black) and mirrored face (grey).

The symmetrical parts fit very well (Figure 7), the asymmetrical differ (Figure 6).

Before and after each injection the symmetry plane was computed. Two resulting planes are displayed in Figure 8.

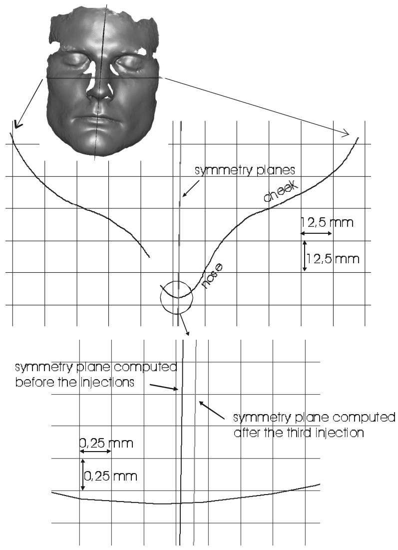

Figure 8: Horizontal cut view of the face and the two symmetry planes.

One symmetry plane (black) was computed based on the measurement before the injection. The other plane (grey) was computed starting from the measurement after the third injection. The angular misalignment is 0.16°. The figure shows that the original symmetry plane was successfully reconstructed in the asymmetric face. In Table 2 all angular misalignments for two test persons are denoted.

angular misalignment	after 1. injection	after 2. injection	after 3. injection
test person 1	0.08°	0.29°	0.16°
test person 2	0.24°	0.07°	0.23°

Table 2: Angular misalignment of the symmetry planes computed after the injections referring to the symmetry plane computed before the injections

We further compared the mirrored faces with the original face. Therefore we mirrored one half of the face at each computed symmetry plane. Afterwards the mean distance and the standard deviation of the distance were computed as described in section 3. The results are shown in Table 3 and 4.

test person 1	mean distance in mm	standard deviation in mm
before injection	-0.19	1.19
after 1. injection	-0.17	1.19
after 2. injection	-0.02	1.22
after 3. injection	-0.17	1.20

Table 3: Comparison between mirrored mesh and original mesh.

There are only little differences in the values of the standard deviations before and after the injections. This demonstrates that in each case the symmetry plane of the original face could be reconstructed in the partly asymmetrical face. The higher standard deviation for test person 1 indicates that the face of this test person is less symmetrical than the face of the other test person.

test person 2	mean distance in mm	standard deviation in mm
before injection	0.05	0.48
after 1. injection	-0.17	0.52
after 2. injection	-0.16	0.52
after 3. injection	-0.18	0.52

Table 4: Comparison between mirrored mesh and original mesh.

5 Determination of the Eye Position

Our final goal is to indicate to the surgeon intraoperatively the correct position of the displaced globe of the eye. Being narcotised, all the muscles of the patient are relaxed and eye movements that disturb the assessment of the globe position do not occur. Thus the correct position for the displaced globe of the eye is acquired by mirroring the actual 3D position of the healthy globe at the computed symmetry plane.

Besides the computation of the symmetry plane it is therefore necessary to automatically determine the 3D position of the eyes.

Unfortunately no sensor data can be obtained of the dark eye pupil. Therefore, contact lenses with matted surface were used. This is approved by the Institutional Ethics Committee of the University of Erlangen-Nuremberg (file no. 2221).

The use of contact lenses in order to measure the position of the globe of the eye has been described previously: Lozano et al. have established a method for radiographical measurements for the accurate localization of the globe using contact lenses [19].

Due to their self-centering design the contact lenses perfectly fit the cornea. Therefore, the center of the lenses coincides with the center of the pupil.

As we obtain for each measurement a 2D video image and an associated range image with the 3D coordinates, we can detect the lenses in the 2D image and afterwards interpolate the 3D coordinates of the pupil center based on the range image. In Figure 9 a range image of a person wearing such contact lenses is depicted.

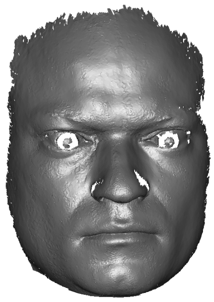

Figure 9: 3D measurement of a person wearing special contact lenses.

In a first experiment we tested these lenses with healthy persons. If the person looks straightforward, the mirrored position of the right eye should coincide with the left eye assuming an adequate determination of the symmetry plane. In Table 5 the deviation of the computed, mirrored, eye position from the measured eye position is given for two test persons.

Deviation of the mirrored position from the actual position	Δx in mm	Δy in mm	Δz in mm
person 1	1.6	-0.9	-0.2
person 2	1.0	-0.6	-0.3

Table 5: Comparison between the actual eye position and the mirrored eye position.

The length of the difference vector between the actual position of eye 1 and the mirrored position of eye 2 is 1.8 mm for person 1 and 1.2 mm for person 2. The angle between the connection vector of both eyes and the normal vector of the symmetry plane is 0.7° for person 1 and 0.6° for person 2. The deviation in x- and y-direction between the mirrored and the measured position is higher than the one in z-direction. The reason for this is that the test persons did not look exactly straightforward. However this problem does not arise for persons being narcotised. Therefore, in a next step we will test this method intraoperatively.

6 Conclusion

In this paper we presented a concept for an intraoperative support of the surgeon during the repair of the displacement of the eye globe.
To compute the nominal 3D position of the globe it is essential to know the symmetry plane of the face. We presented a method to compute the symmetry plane. This method is based on registration algorithms.
We tested the method on healthy persons and found out that the mirrored face matches the real face very well. Furthermore, we investigated to what extent asymmetric parts in the face affect the computed symmetry plane. The symmetry plane of the previously symmetrical face could be reconstructed in spite of the asymmetric parts. Finally, we described how we determine the 3D position of the eye. The next step will be to extend the number of test persons in order to validate the results.

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