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Automated detection of alveolar arches for nasoalveolar molding in cleft lip and palate treatment

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Abstract: Nasoalveolar moulding (NAM) has become a widely accepted and evidence-based treatment strategy for newborns with cleft lip and palate (CLP), attempting to reduce the cleft gap and to form an appropriately shaped alveolar arch by an intraoral patient-specific NAM plate and to erect the usually flattened nostrils towards a natural nose wing occurrence. The generation of such an appropriately shaped NAM plate requires, besides 3d information of the patient's initially cleft lip and palate, an estimated target model of the maxilla. Previous studies showed the applicability of curve-based approaches to describe the maxilla during early infancy. We have developed an automated algorithm implemented with the programming language Python, describing the alveolar arch by an approximated ellipse. Therefore, the digitalized data sets of human maxillae were aligned to a global coordinate system with a total least square method and subsequently analyzed with the curvature-based algebraic point set surfaces (APSS) algorithm. The gathered information of height ratio and curvature allows the detection of points on the alveolar segments and therewith the fit of an ellipse describing the human maxilla. In 84.5% of 193 maxilla impressions of healthy newborns the fitted ellipses described the course of the maxilla within defined margins. Applying the algorithm to 38 newborns suffering from unilateral cleft lip and palate in 76.3% the fitted ellipses bridge the CLP alveolar segments, so that a harmonic alveolar arch can be deduced. Describing the alveolar arch by one or multiple ellipses allows (i) to automatically measure the dimensions of the maxilla, (ii) to derive a growth model during early infancy, (iii) to derive a healthy harmonic arch from CLP alveolar segments and (iv) to automatically generate a basic NAM device on the basis of the virtually modified maxilla.

Keywords: algebraic point set surfaces; alveolar arch; cleft lip and palate; rapidNAM; quadric edge collapse decimation.

1 Introduction

Cleft lip and palate, with its occurrence of 1:500, is amongst the most frequent inborn deformities. The many-sided forms of appearance of CLP require a complex treatment, such as the Nasoalveolar Moulding (NAM) therapy introduced by Grayson and Wood [1]. NAM allows to (i) align the alveolar segments by an intraoral NAM plate in order to obtain an appropriately shaped alveolar arch and (ii) to erect the usually flattened nostrils towards a natural nose wing occurrence. Recent studies emphasize the success of NAM therapy in terms of a decrease in necessary secondary revision surgeries and therewith the cost of care [2, 3]. Opponents of NAM criticize the time-consuming and cost-intensive therapy, since the intraoral plate needs to be weekly adopted to fit the patient's growing maxilla [4]. An approach to overcome this drawback of this therapy facilitates the generation of the intraoral plate through automation. Therefore, the Department of Oral and Maxillofacial Surgery and the Institute of Medical and Polymer Engineering of the Technical University of Munich launched the RapidNAM project, to obtain an automated workflow to generate the intraoral plate 3 months in advance on the basis of an initially taken impression, involving a growth prediction factor [5]. To generate NAM plates in advance and to obtain the growth of maxillae in newborns, the maxillae need to be measured and described in a mathematical form. Taking different shapes of alveolar arches into account, ellipses allow to describe these different shapes.

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2 Material and methods

For the development of the following algorithm, at least six impressions of 32 healthy neonates' maxillae were taken on a monthly basis during their first 6 months of life. The taken impressions were digitalized with a 3-dimensional triangulation scanner (3Shape D700, 3Shape A/S, Denmark) with a resolution of 20 µm and saved in .stl format. The algorithm to fit ellipses to the alveolar arches was implemented in the programming language Python (Python Software Foundation, version 2.7, Netherlands). The algorithm is subdivided in a preprocessing, a main processing and a postprocessing unit (see Figure 1).

The preprocessing unit creates a class for each patient and its attributes with subclasses for each taken impression. The Quadric Edge Collapse Decimation (QECD) algorithm optimizes the relation between the reduction r in percent of the number of triangles for each model and the preservation of 3d geometrical information [6]. Thus, an equilibrium between minimal computing time and best quality output can be reached. To allow for comparison and analysis the digitalized models were rotated using a total least square algorithm so that the x-axis is aligned along the palatine raphe and the z-axis is perpendicular to the palate. The model is reoriented, in case of a misalignment.

The main processing unit determines a certain amount of points on the alveolar arch, which are used to fit an ellipse to the maxillae. Therefore, the amount of relevant points for the fit is consecutively restricted following the subsequent criteria: First, only points with a higher z-coordinate than a level value, determined by the centre of gravity and the highest point on the alveolar arch, are taken into consideration. Thus, the base of the cast can be divided from the relevant alveolar segments. Subsequently the curvature was calculated by a spherical fit for the lasting points, to determine the points of the alveolar ridge, which have a significant normalized curvature. Therefore, the algebraic point set surfaces algorithm was implemented [7, 8]. This algorithm provides a robust estimation of the mean curvature by fitting a sphere approximating the local surface at any given point p_i. The local environment at point p_i is evaluated by a weight function $w_i(x)$:

$$w_i(x) = \emptyset\left(\frac{\|p_i - x\|}{r_i {}^\star h}\right) \tag{1}$$

Here, $\emptyset$ is a smooth, decreasing weight function and h is a scale factor defining the influence of the radius r_i at every point. This radius is computed calculating the distance from a given point to its k-nearest neighbour. Following, solving an eigen problem provides the coefficients of the locally fitted sphere. The mean curvature can now be calculated by the inverse of the radius of the fitted sphere.

The alveolar ridge is radially subdivided in n segments with the center of gravity as its center of rotation, to obtain a point for each segment on the alveolar arch, which fulfills the stated criteria. A distance check from each point to its next neighbours and to the center of gravity deletes possible outliers.

The postprocessing unit, fits a 2-dimensional ellipse to the determined points on the alveolar ridge, neglecting the 3^{rd} dimension.

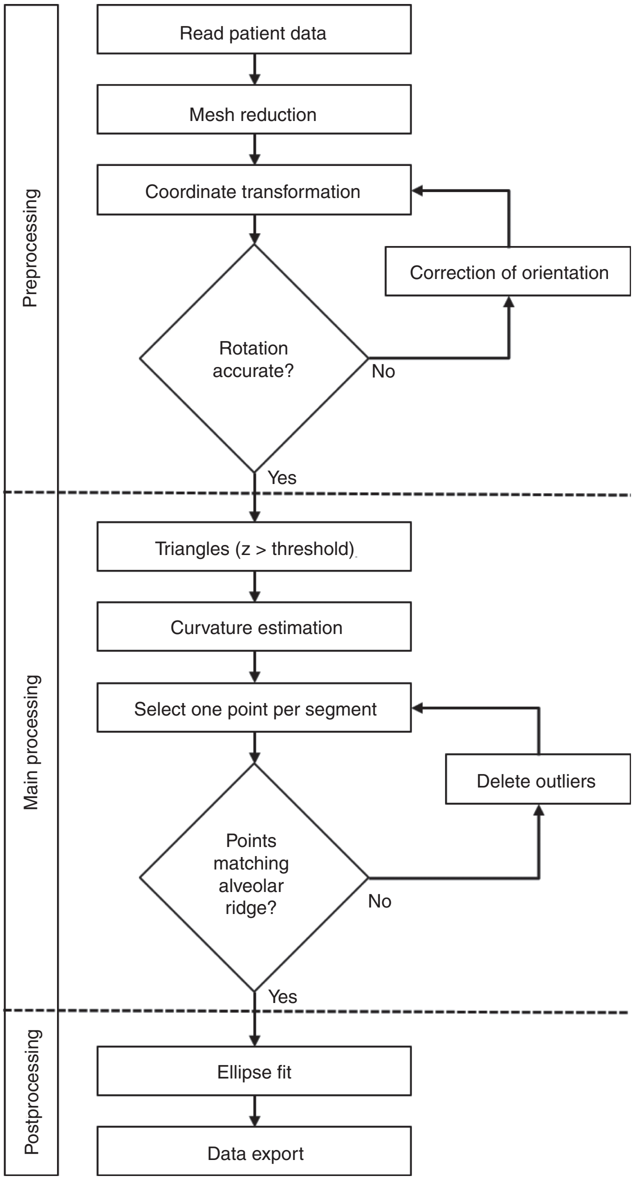

Figure 1: Program flow chart to describe the course of human maxillae during early infancy using ellipses.

The same algorithm was used to determine ellipses for unilateral cleft lip and palate patients. Therefore, the parameters of the APSS and the z-threshold were adopted. Furthermore, for the cleft region no points could be found and the ellipses were fitted on the basis of the selected points on the two alveolar segments.

Since the fitted ellipses are meant to derive a closed and harmonic alveolar arch from a CLP patient's impression, the quality of the automated determined ellipses was evaluated. Therefore, the automated determined ellipses were qualitatively compared with manually found ellipses, which were determined by a medical doctor on a basis of manually selected anatomical reference points on the alveolar arch.

3 Results

The total number of elements for one digitalized impression was in a range of 250,000 to 300,000 triangles. This led to a long computing time, even though only selected elements were used for the curvature calculation. The QECD algorithm was implemented and tested for 54 impressions of healthy maxillae. Thereby, a mesh reduction of 95% was found to perform best in terms of computing time versus loss of 3d information (see Table 1). The maximum and root mean square deviation were determined in Meshlab (Visual Computing Lab ISTI – CNR, Italy) with the unilateral Hausdorff distance [9, 10]. Qualitative comparisons show that the mesh reduction does not influence the position and form of the fitted ellipse.

The k-nearest neighbour for the curvature calculation was set to $k = 5$, which defines a spherical radius depending on the distance from a point to its 5th next neighbour. This allows us to separate the alveolar ridge from the remaining parts of the impression, due to a significant difference in its normalized curvature.

Analysing 193 taken impressions of maxillae of healthy patients lead in 84.5% to an ellipse, which describes the harmonic course of the alveolar arch (see Figure 2). In 27 cases the ellipse did not describe the alveolar arch and in three cases an ellipse could not be fitted. In comparison, in 30.5% of all taken impressions the medical doctor could not determine anatomical points on the alveolar arch, due to poor quality of the impression.

Table 1: Effect of QECD algorithm on process parameters at a mesh reduction of 95%.

	Original	QECD
Computing time (s)	650 ± 147	1.6 ± 0.25
File size (MB)	200 ± 16.8	6 ± 0.8
RMS deviation (mm)	–	0.0038 ± 0,0002
Max deviation (mm)	–	0.0678 ± 0.0179

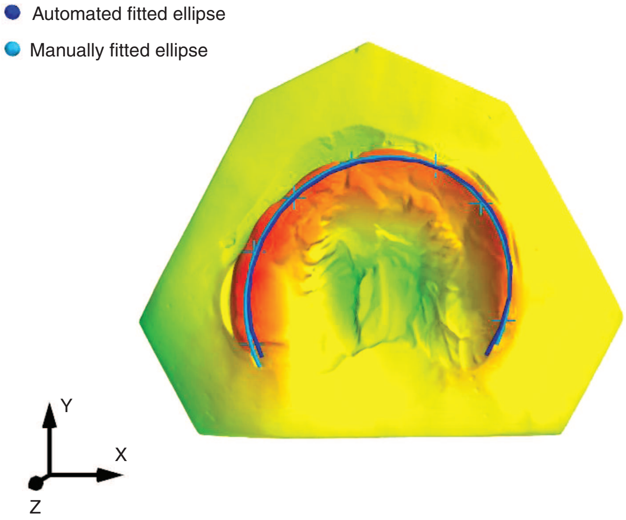

Figure 2: Comparison between the fitted ellipses to the automated determined points (blue) and the manually selected points (cyan) on the alveolar arch of a 2 month old patient.

Qualitatively comparing the fitted ellipses on the basis of automated determined and manually selected points emphasises the applicability of the algorithm to detect the course of the alveolar arch (see Figure 2).

To fit ellipses to the maxillae of 38 impressions of 18 patients suffering unilateral cleft lip and palate, a slightly adopted algorithm was used and bridged in 76.3% the two alveolar segments towards a harmonic course of the maxillae (see Figure 3). For five models the ellipse did not describe the course of the alveolar segments due to outlier points or incomplete detection of the alveolar segments. In four cases a fit of an ellipse could not be achieved.

4 Discussion

The mesh reduction algorithm QECD allows to significantly reduce the computation time and file size at a reasonable deviation of mesh accuracy, since the impression-taking is subject to a higher influence [11].

The impression-taking process highly influences the quality of the found ellipses, since artefacts on the surface of the impressions may lead to outliers, since curvature and z-coordinate indicate their belonging to the alveolar arch. This effect occurs mainly in the dorsal section of the impressions, because the outlier detection is distance-based from the centre of the impression.

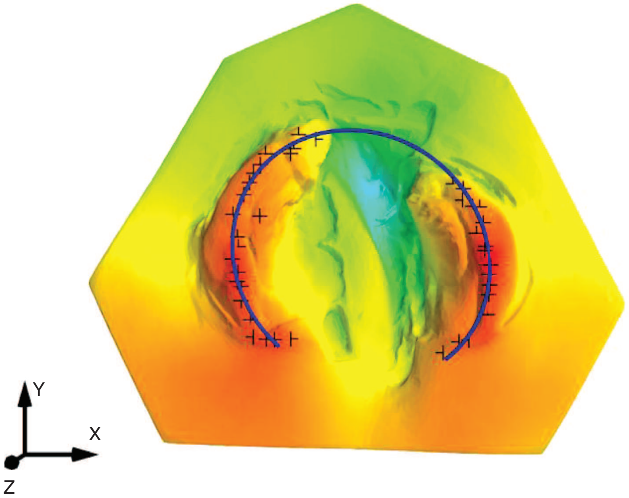

Figure 3: Fitted ellipse to automated determined points on the two alveolar segments of a newborn unilateral CLP patient ($r = 0.95$, $k = 2$, $n = 30$).

The k-nearest neighbour parameter k is highly dependent on the mesh reduction parameter r, since the spherical radius r_i is derived from the k-nearest neighbour parameter. Hence, a finer mesh leads to a lower spherical radius at the same k-nearest neighbour parameter. Even though an ideal parameter set would be determinable, all healthy and CLP impressions were analysed with the same set of parameters. The subdivision in n segments was increased for the CLP patients to obtain more points on each alveolar segments.

5 Conclusion

The presented algorithm allows to fit ellipses, describing the course of healthy and CLP patients' maxillae. These findings are consecutively used to determine a growth prediction factor of human maxillae. The growth prediction factor is meant to be integrated in an automated generation process for NAM plates. This allows us to generate patient-specific NAM plates in advance using the determined ellipses to model the CLP segments towards a harmonic arch. Thus, NAM plates can be generated up to 4 months in advance on the basis of a first impression taken after birth. Thereby, the burden on the patients, the parents' of the patients and the clinicians in terms of time-consumption and costs can be reduced.

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