Reconstruction of mandibular dysplasia using a statistical 3D shape model

Stefan Zachow [a,*], Hans Lamecker [a], Barbara Elsholtz [b], Michael Stiller [b]

[a] *Zuse-Institute Berlin (ZIB), Takustraße 7, D-14195 Berlin*

[b] *Zentrum für Zahn-, Mund- und Kieferheilkunde, Universitätsklinikum Charité Berlin, Campus Benjamin Franklin*

Abstract

A statistical 3D shape model of a regularly developed human mandible is presented. The shape model (often referred to as an atlas) is created from 11 tomographic data sets, representing a mean mandibular shape including all of its variations to any shape of the underlying training set. The atlas will serve as a foundation for the reconstruction of missing or malformed bony structures. First preliminary results are presented for three different cases of distinct mandibular deformities, and it is shown, that such a 3D shape model might provide a reasonable basis for the planning of a surgical reconstruction. Hence, the atlas will be extended by at least 140 available data sets that have been acquired using a NewTom DVT.

Key words: surgery planning, mandibular reconstruction, statistical shape model, optimization

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1. Introduction

Patients with distinct craniofacial deformities or missing bony structures require a surgical reconstruction that in general is a very complex and difficult task. The main reasons for such malformations, as show in Figure 1, are tumor related bone resections or craniofacial microsomia [1, 2]. In cases where the reconstruction cannot be guided by the symmetry of anatomical structures, it becomes particularly challenging. Then a surgeon must compare the individual pathologic situation with a mental image of a regular anatomy to modify the affected structures accordingly. For such a surgical therapy osteotomies are typically performed with either subsequent osteodistraction [3] or osteosynthesis after relocation of bony segments [4], sometimes even in combination with selective bone and soft tissue augmentation. In more than 15 cases of mandibular dysplasia and hemifacial microsomia that we have planned so far [5, 6], any kind of guideline for the perception of a designated objective was highly desired. Hence, the aim of our work is to provide a statistical 3D shape model of a human mandible, that will serve as a template for individual treatment planning. Depending on gender and age, different models might be developed as well.

* Corresponding author.
Email addresses: `zachow@zib.de` (Stefan Zachow), `lamecker@zib.de` (Hans Lamecker).
URL: `www.zib.de/visual/projects/cas` (Stefan Zachow).

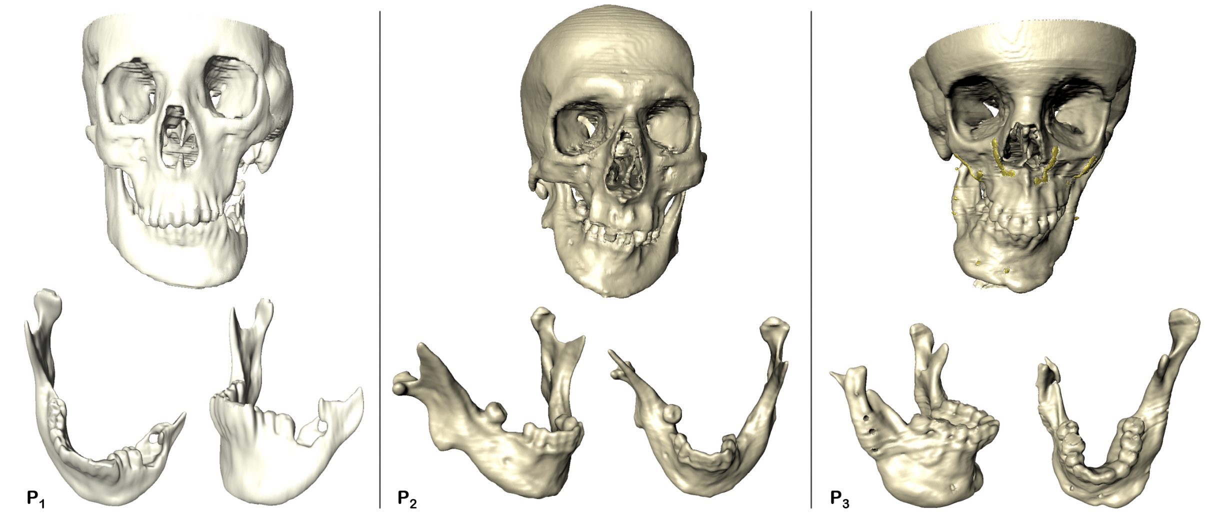

Figure 1. Three cases of hemifacial microsomia with evidently malformed mandibles

A statistical 3D shape model represents a mean shape including all of its variations to any shape of the underlying training set. In our case it will be derived from a large set of regularly developed mandibles, reconstructed from tomographic data. First preliminary results are presented within this work, demonstrating that a representative model might provide a reasonable basis for surgical reconstruction of distinct mandibular deformities.

2. Material and Methods

In a feasibility study we created a preliminary statistical shape model of a human mandible, that is derived from 11 individual CT data sets (training set). Each of the reconstructed mandible geometries is mapped onto a common reference shape to identify corresponding points (Fig. 2 b), thus allowing the representation of each surface model in a common vector space [7]. This transformed training set is subject to subsequent statistical analysis via Principle Component Analysis (PCA). The goal of PCA is to represent as much variance contained in the training set by as few parameters as possible. These essential degrees of freedom of the resulting statistical model enable us to explore characteristic mandibular shapes within a normal variation, and to reconstruct new shape occurrences by linear interpolation of all or just a few selected eigenmodes (i.e. major modes of variation). Hence, the 3D mandible model can serve as a template for surgery planning, by finding an optimal fit of any of its variations to a given malformed mandible.

2.1. *Correspondence Maps*

Each of the mandible models is decomposed into a set of corresponding patches, being homeomorphic to a disk (Fig. 2 c). We chose a separation of the condyles and the horizontal and vertical branches on each side. For symmetry aspects, the entire mandible is split in half, subdivided through the lower frontal incisors. In order to separate the variability of an individual dentition from the shape of the bone, the tooth region was assigned its own patch. Each pair of corresponding patches on two different surfaces is finally parameterized to a common base domain (in our case a disk) by minimizing metric distortion. To achieve continuity across patch borders, the patch boundaries are mapped to the base domain according to their average arc-length on the two surfaces.

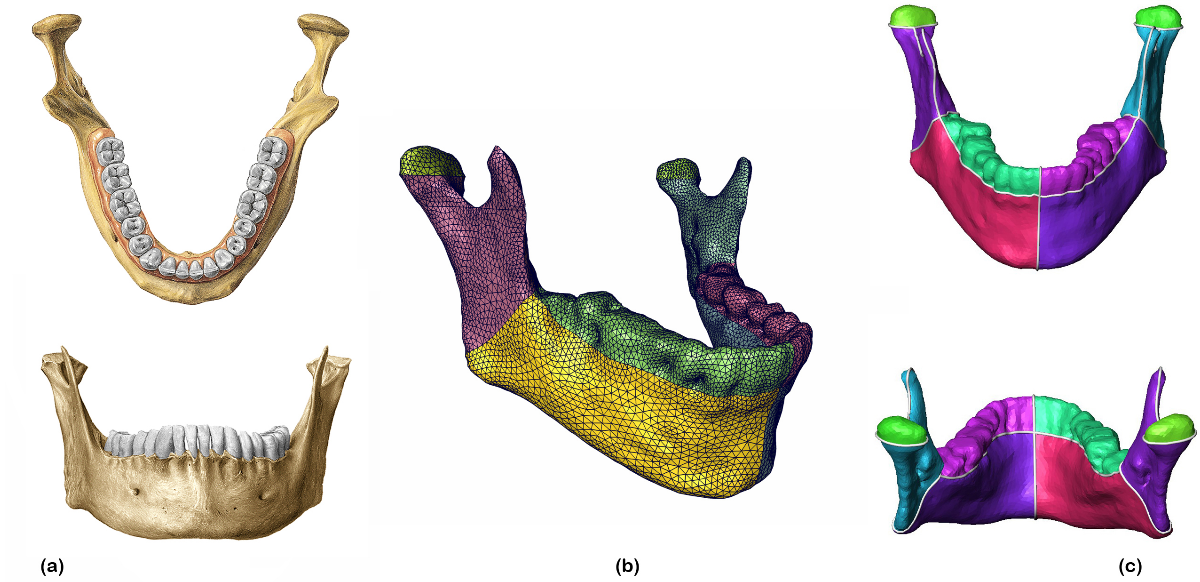

Figure 2. a) Mandibular anatomy, b) reference mesh, c) patch decomposition

2.2. *Statistical Shape Model*

After computation of the correspondence maps and subsequent alignment, each of the mandible surfaces can be represented by a vector $\mathbf{v}_i$ in a $3m$-dimensional vector space. Here, m is the number of sample points of the reference mesh, and $i = 1, \ldots, 11$ counts the number of mandible surfaces in the training set. PCA yields an averaged shape $\overline{\mathbf{v}}$ of all representatives contained in the training set, including the most characteristic modes of variation $\mathbf{p}_k$. These so called eigenmodes are arranged according to the magnitude of their eigenvalues $\lambda_{k+1} > \lambda_k$. Any legal instance of a mandible shape $\mathcal{S}$ within this analysis may now be generated by linear combination of the eigenmodes: $\mathcal{S}(\mathbf{b}, T) = T\left(\overline{\mathbf{v}} + \sum_k b_k \mathbf{p}_k\right)$, where T denotes a rigid-body transformation (cf. Fig.3).

2.3. *Template for Surgical Reconstruction*

For pathologic cases, as shown in Figure 1, the goal is to determine a rigid-body transformation T in combination with the shape weights $\mathbf{b}$ so that the 3D shape model $\mathcal{S}$ matches the healthy part of the mandible as accurate as possible. This is achieved by selecting parts of the mandible that are considered as being regularly shaped and therefore are to be preserved. For these selected regions the root-mean-squared surface distance d_{rms} between the shape model and the individual mandibular shape is minimized: let $d(\mathbf{x}, \mathcal{S}') = \min_{\mathbf{x}' \in \mathcal{S}'} \|\mathbf{x} - \mathbf{x}'\|_2$ denote the distance of a point $\mathbf{x}$ on a surface $\mathcal{S}$ and the surface $\mathcal{S}'$. For the best match, we minimize the symmetric distance

$$d_{\text{rms}}(\mathcal{S}(\mathbf{b}, T), \mathcal{S}') = \sqrt{\frac{1}{|\mathcal{S}| + |\mathcal{S}'|}\left(\int\limits_{\mathbf{x} \in \mathcal{S}} d(\mathbf{x}, \mathcal{S}')^2 d\mathcal{S} + \int\limits_{\mathbf{x} \in \mathcal{S}'} d(\mathbf{x}, \mathcal{S})^2 d\mathcal{S}\right)}.$$

with respect to $\mathbf{b}$ and T via a quasi-Newton optimization method [8]. Thus, the adjusted statistical shape model can serve as a 3D template for the reconstruction of a malformed mandible.

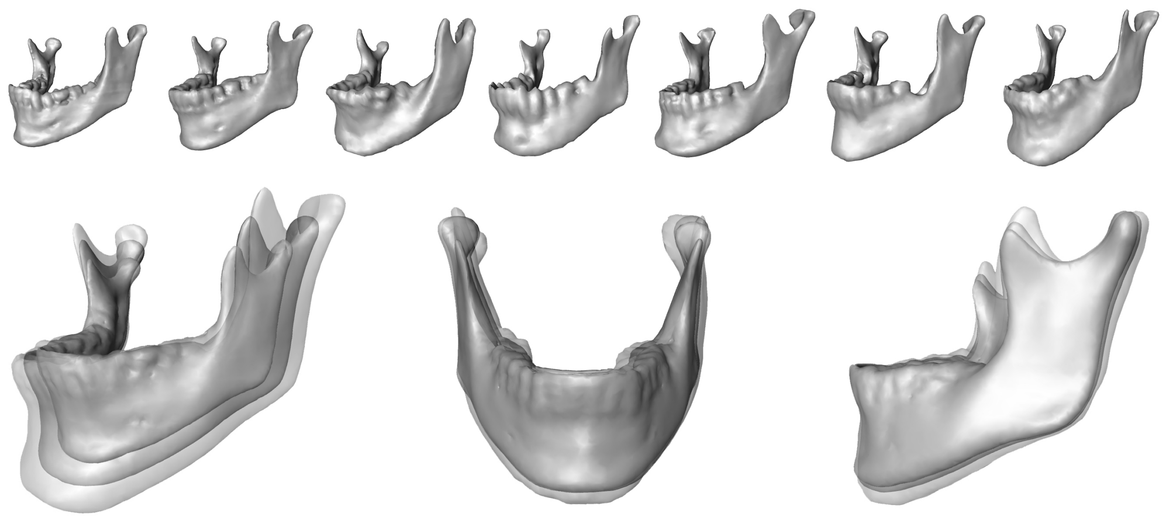

Figure 3. top) selection of different shapes of the training set, bottom) three major modes of variation of the mean mandible

3. Results

At the moment our statistical shape model is made of 11 mandibles only. However, first experiments with this rather small amount of mandibular shape samples already show a broad range of typical variations. With only 10 characteristic shape modes we are able to distinguish between the height of the rami mandibulae, the mandibular angle, the length of the vertical branches, the width of the entire mandible, the radius of the mandibular arch, the shape and the size of the condyles. After optimization of the rigid transformation T in combination with the shape weights $\mathbf{b}$ with regard to a minimal distance d_{rms} between the relevant part of the mandible that is to be reconstructed and the shape model, a mean distance d_{mean} between 1.2 and 1.5 mm with a median of 1.0 to 1.2 mm was achieved (cf. Tab. 1). For more than 70, up to 83 % of the selected surfaces the deviation was below 2 mm, and only 2 – 6.5 % of the surfaces were deviating more than 4 mm. The maximum distance of 8.3 – 10.4 mm between the adjusted shape models and the individual mandibles originates from the fact, that a statistical shape model consisting of only 11 samples is far from being representative to describe all variations of a human mandible. However, the value for d_{max} is expected to diminish with a larger training set.

Table 1
Statistics on the deviation between the surfaces of the shape model and the malformed mandible within a region of interest

Patient	d_{mean} [mm]	d_{median} [mm]	d_{max} [mm]	$d_r(2\,\text{mm})$ [%]	$d_r(3\,\text{mm})$ [%]	$d_r(4\,\text{mm})$ [%]
P_1	1.2	1.0	10.4	16.8	5.0	2.0
P_2	1.4	1.0	9.2	22.7	11.4	6.4
P_3	1.5	1.2	8.3	29.0	13.5	5.8

For each of the three pathological cases in Figure 1 we were able to find a suitable candidate from our statistical shape model, using the optimization described in section 2.3. An example for the first patient is shown in Figure 4. The morphological difference of the optimally aligned two shapes can be measured in size and volume, thus either indicating the thickness of bone augmentation or being suited as a template for autologous bone grafts, the configuration of titanium plates or even the fabrication of individual prostheses.

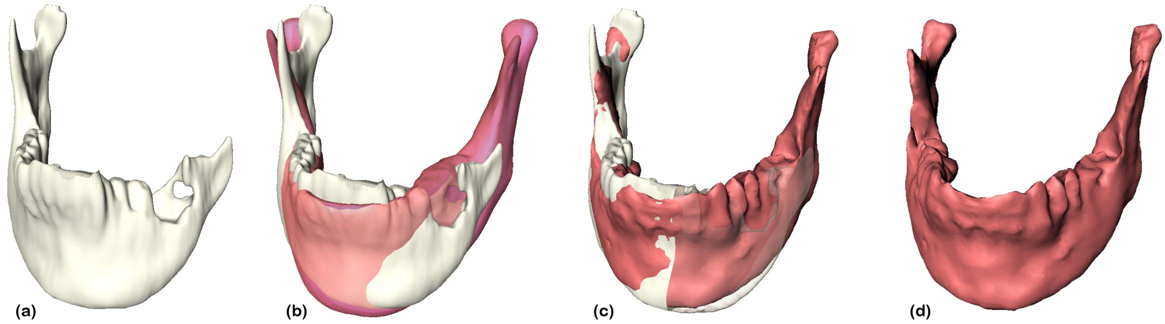

Figure 4. Template generation for patient P_1, see table 1: a) hypoplastic mandible, b) mean mandible shape, c) adaptation of the shape model to the right part of the mandible, d) 3D template for mandible reconstruction

With our preliminary study we could demonstrate that a statistical shape model of a human mandible can be build from a set of individual mandibular shapes. In order to improve our shape model, 140 suitable data sets have been chosen, that were acquired for dental implant planning, using a NewTom DVT. These data are currently segmented using the AMIRA software [9]. Each reconstructed mandible will be decomposed in the same manner as described in section 2.1, thus contributing to the variation of the statistical shape model. We expect, that with an increasing number of regularly shaped samples we are able to distinguish between all significant variations of the human mandible. In addition we are going to incorporate the mandibular nerve into the shape model as well, to study the relationship between the shape of a mandible and the location of the nerves.

4. Conclusion

A statistical 3D shape model of the human mandible has been presented, that seems to be a valuable planning aid for surgical reconstruction of bone defects. This is particularly useful for severe cases of hemifacial microsomia, as shown in our three examples. With a best matching candidate of the shape model, regarding the size and the shape of available bone, a surgeon gets a good mental perception of the reconstruction that is to be performed. The method of statistical shape modeling can be used for other bony structures as well, as it is investigated by our group for the planning of surgical corrections of craniosynostoses [10].

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