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Development of a Statistical Shape Model of the Zygomatic-Maxillary Complex as Input to Plate Design Optimization

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Abstract

Introduction The aim of this study was to develop a statistical shape model of the zygomatic maxillary complex (ZMC) to assist in the development of a preformed 3D osteosynthesis plates for surgical treatment of zygomaticomaxillary complex (ZMC) fractures.

Methodology A statistical shape model (SSM) was build using 53 CT scans of patients who sustained and were surgically treated for a unilateral ZMC fracture. The unaffected side was used to build the SSM. The new element in the build was the development of a reference template of the bony area of interest that could be mapped to all individual meshes using initial correspondence mapping. After that only the region of interest for an osteosynthesis plate (as set by the template) was used to capture the variation of the ZMC.

Results The first 10 principal components explained >95% of the model's variance. The generalization demonstrated a mean error of 0.53 mm for the complete model. The largest variations (up to 4.5 mm) occur in the teeth area, the zygomatic arch and the medical side of the inferior orbital rim; and smaller variations (<0.2 mm) occur in the zygomatic center area.

Conclusion The SSM is gives quantitative information for the design of preformed 3D osteosynthesis plates for the ZMC, and the methods could be applied for shape analysis of other bony regions that are less defined.

1 Introduction

The zygomaticomaxillary complex (ZMC) provides structural support, facial symmetry, and forms part of the orbit and cheek, crucial for protecting the eyes, enabling chewing, and supporting facial expressions [1]. ZMC fractures account for 22% of facial trauma cases commonly resulting from interpersonal violence, falls, traffic accidents or contact sports [2]. Surgical treatment aims to restore normal facial contour, reestablish orbital volume, and ensure proper alignment of the zygoma with adjacent structures to recover function and achieve skeletal symmetry [3]. For displaced fractures, osteosynthesis plates with screw fixation are used to stabilize the fracture [4]. However, the complex anatomy of the zygoma and the variability in fracture patterns contribute to relatively high complication rates, with approximately 10% of cases requiring a revision surgery [5].

Over the last two decades, preformed 3D stock osteosynthesis plates have been developed and have gained significant popularity for the reconstruction of the orbit and the mandibula demonstrating favorable outcomes, improved mechanical stabilization and a reduction in stress fractures or plate loosening [6]. In line with this development [7], we aimed to perform a shape analysis of the ZMC to give crucial input for development of preformed 3D ZMC plates.

2 Methodology

CT-scans of 53 patients representing the target group were used to build the SSM. These patients (43 male, mean age 41.9 years) all had sustained a unilateral ZMC fracture, and were treated using a primary open reduction and internal fixation in the Amsterdam University Medical Centre between 2011-2023.

The challenge in building the zygoma SSM was that the ZMC is not a well-defined closed object, thereto we generated a reference template to select zygomatic regions of interest.

Step 1: Segmentation

The CT data were segmented using the atlas-based algorithm available in Brainlab Elements (BrainLAB AG, 2001 Germany) which contained the zygoma and maxilla bones separately. The unaffected maxilla and zygoma bones were subsequently fused with a boolean union operation. Finally, the maxillary sinus was filled, as we were only interested in the outer bony surfaces.

Steps 2&3: Preprocessing and initial alignment

The resulting .stl-files were remeshed using MeshMixer (Autodesk, 2020, California, USA) with a target edge length of 0.75 mm, instead of a uniform number of vertices to provide consistency in remeshing effects between data sets. Subsequently, the 53 meshes were aligned in 3DMedX (Radboudumc, 2023, Nijmegen, The Netherlands) using the iterative closest point algorithm aided by the following landmarks for initial alignment: a landmark between dacryon and alare (at the level of the infraorbital foramen), the anterior nasal spine (ANS), zygomaxilare, and infraorbitale (Figure 1). The landmarks were distributed to capture the dimensions of the area of interest, while being easy to indicate.

Step 4: Initial correspondence mapping

From the resulting .obj-files, a single mesh was chosen to serve as initial reference template. From this mesh, the teeth were excluded and the paranasal bone opened. Subsequently, the MeshMonk

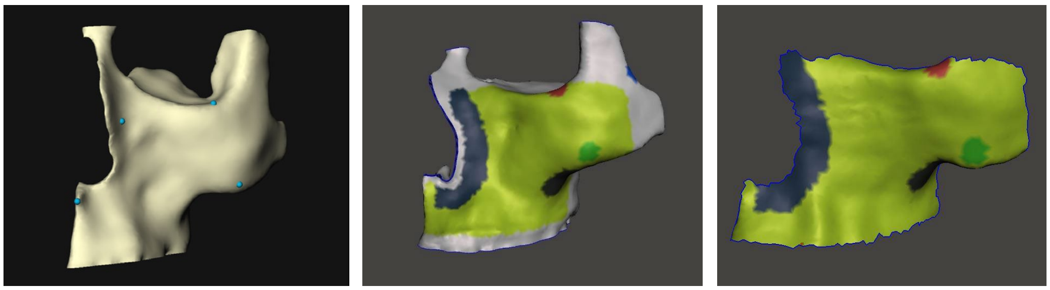

Figure 1: Left**:** Blue sphere indicate the landmarks use for initial manual alignment. Middle: Final reference template model used to extract the colored region of interest from all patient meshes to build the zygoma SSM. Right: Extracted area of interest to build the ZMC SSM.

algorithm was used to generate the correspondence between the first 9 patient meshes and the reference template [8]. The average mesh of these 10 aligned and corresponding patient meshes was set as the reference template to establish point correspondence between all meshes using 3DMedX. A region of interest (ROI) plate fixation was defined (colored area) within the reference template, and easily identifiable regions (paranasal, infraorbitale, zygomatic prominence, transition maxilla-zygoma) were indicated in different colors to visually verify the correspondence mapping.

Step 5: Extracting region of interest

Using MeshMixer, the surface regions not included in the region of interest were removed.t (Figure 1).

Step 6: Building the SSM

The open-source code of Scalismo (Scalismo v0.92, 2024, University of Basel, Switzerland) was used to process the extracted ROI and create an average shape of the zygoma bone region[9]. Subsequently, a principal component analysis was performed to highlight the variations.

Performance of the SSM was evaluated on generalization, compactness and specificity [10]. Finally, the regions showing least and most variation are highlighted.

3 Results

The generalization of the SSM demonstrated a mean error of 0.53 mm if all principal components in the leave-one-out setting were included (Figure 2A). The compactness is represented by the first 10 principal components representing over 95% of the found variance (Figure 2B). The specificity results range from 0.9 to 2.6 mm (Figure 2C). Figure 2D visualizes the average shape of the zygoma region and the areas with larger (up to 4.5 mm) and smaller variations (<0.2 mm).

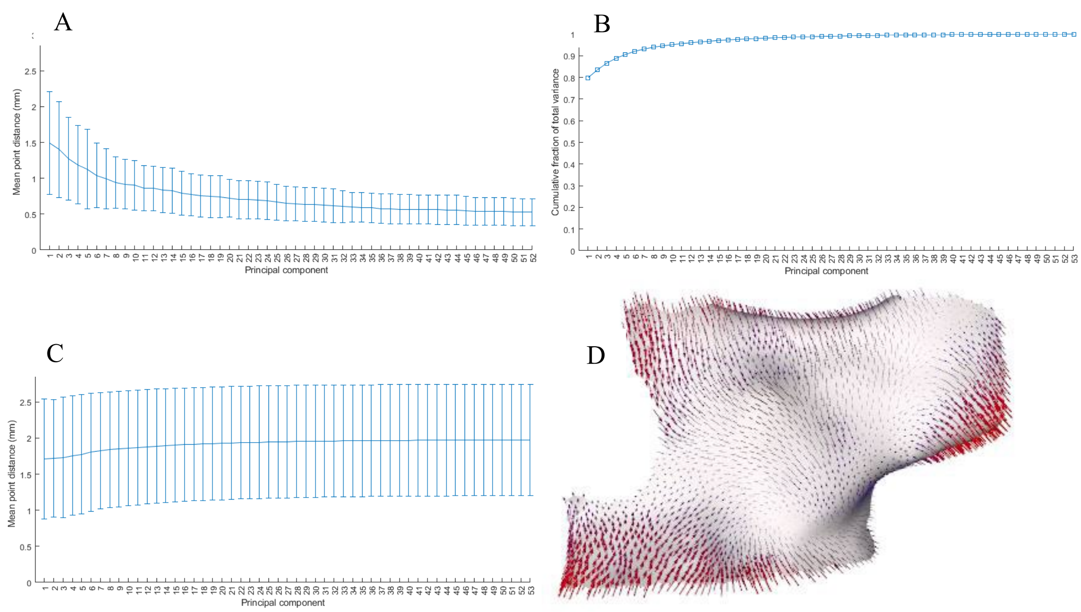

Figure 2: Results of the generalization (A), compactness (B) and specificity (C). Average shape of the zygoma region (D) showing the areas with large variations (red arrows) and small variations (blue).

4 Discussion

A statistical shape model of zygomaticomaxillary complex (ZMC) was successfully built by using various software packages and algorithms in combination with expert knowledge of zygoma anatomy and fractures to generate a reference template to only include regions of interest. Although the data set of 53 patients seemed a bit on the low side, the SSM performed sufficiently according to the evaluation parameters [11]. The SSM captures shape variations with an accuracy higher than the natural variation in shape symmetry of the zygomaticomaxillary complex [12].

The results give sufficient confidence to discuss input for the design of preformed osteosynthesis plate(s).The maximum variations are found in areas that may be of lesser importance for shape compliance of the plate, because fractures are typically absent in those regions and it may not be necessary to extend the plate to these regions The central area of the region of interest - that is prone to fracturing - shows limited variation. The ZMC SSM thus gives quantitative and qualitative information for the design of preformed 3D osteosynthesis plates, but should be combined with clinical information (bone thickness, surgical access) and material property parameters to obtain an optimal preformed osteosynthesis plate for treating ZMC fractures.

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