Optimization in model-based simulations of surgical procedures - Surgically Assisted Rapid Maxillary Expansion

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Summary

Individual and high standardized surgical interventions in cranial and maxillofacial surgery based on a 3-dimensional FEM-model are a new method to improve quality of therapy. Optimization of specific data which based on 3D- finite element analysis could force a fully customized surgery in a minimal invasive way. We evaluate the biomechanical effects of surgically assisted rapid maxillary expansion (SARME) by bone borne intraoral distraction device. An asymmetric distraction with different moving of the both maxillary parts is a well-known adverse effect which base on the individual asymmetry of bone structure, density and geometry.

The model construction based on spiral computed tomographic (CT) scan of a 21-year-old man. Finite Element Analysis (FEA) was created to depict the physiological changes and stress distribution in the cranio-maxillary bone complex. The distraction was performed on the middle intersection line of maxillary symphysis, the maxillary buttress and the pterygomaxillary sutures in different limitations. The mechanical response in terms of displacement and von Mises stresses was the input for optimization. So an iterative cycle generated the optimal parameter of osteotomy for the distraction. We transferred our results to the operation room with a template and performed the osteotomy with piezo-surgery device. With a transpalatal distractor (TPD) we performed the widening of the maxilla.

Generally high stress levels were observed in the FEA under the basal plates of distractor, in paranasal, zygomaticoalveolar and pterygomaxillary area. The measurement of the distraction from the midline was extremely symmetrical.

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With 3D analyzing of CT-scans there is a valid possibility to recognize individual stress distributions in SARME patients using TPD. Extend of osteotomy is individual and depend on stress level of connecting bone structures. Using FEA and optimization strategy in a preoperative analysis we could perform the surgical process symmetrical with reduction of negative side effects.

Keywords: Finite element analysis, Optimization, Distraction, SARME, Simulation

1 Introduction

Transversal compression and maxillary hypoplasia in adults is seen in nonsyndromal and syndromal patients. In skeletally matured patients the uni- or bilateral transversal compression can be corrected by means of a surgically assisted rapid maxillary expansion (SARME). The treatment is a combination of orthodontics and surgical procedures and provides dental arch space for alignment of teeth. The procedure also causes a substantial enlargement of the maxillary bone base and of the palatal vault. The free space is needed mainly in the middle, so in cases with bilateral transversal compression of the maxilla. In unilateral compression or hypoplasia must be increased predominantly a jaw half.

Distraction osteogenesis is a treatment often used in orthopedics and plastic surgery, but more frequently in maxillofacial surgery. There is a variety of distractors available for use on the different parts of the maxillofacial skeleton.

Since early in the 20th century various techniques have been developed for SARME. The main considerations have opposing interests. One side is a more invasive technique with maximal mobility of the maxillary halves for correction over larger distances with less force but with more possible complications The other side is less invasive with less possible complications but with more relapse, more periodontal problems, and unexpected fractures (Holberg et al. 2007).

The midpalatal suture is historically considered the major place of resistance but this was proven to be untrue by Isaacson and Ingram 1964, Isaacson et al. in 1964 and Kennedy et al. in 1976. A disadvantage of the known methods of intraoral distraction is the poor predictability of the result. Vector of distraction and displacement of the bone parts are subjected to many influences. Some of these factors are known as insertion of distraction force, force application and type of osteotomy. Other influencing factors are largely unknown, such as the geometry of the bone, thickness and density of the bone or soft tissue influences.

A wide variety of techniques and methods to correct transverse maxillary hypoplasia is used without underlying scientific basis. Yet another factor might be the tipping of the maxillary segments instead of parallel expansion due to the different position of the dental-borne and bone-borne distractors relative to the ‘center of resistance’ (Brown et al. 2000, Pinto et al. 2001). This ‘center of resistance’ is a combination of the area where the maxillary halves are still connected to the skull after the corticotomy, the pterygoid region, and the resistance of the surrounding soft tissues. An exact control of intraoral distraction is need.

2 Methods

A 21 years old man with a bilateral transversal compression of the maxilla and frontal open bite was treated with a combination of orthodontics and SARME. The dental arch in the anterior region is pointed and not round. The dental arch in the rear region is too narrow for the lower jaw. In figure 1 the plaster model demonstrates the dental position with a tipping of the maxilla, dental rotations and a narrow dental arch.

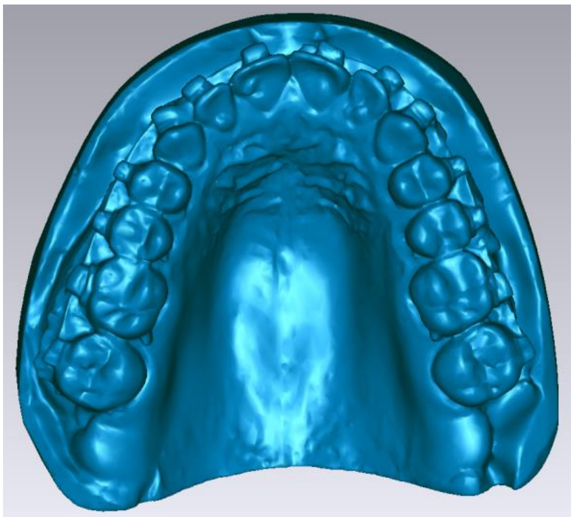

Figure 1: Plaster model of the maxilla

Preoperatively we performed an FEA analysis of the bone model. Therefore we prepared the Dicom data from the CT scan of the scull with mimics® software from Materialise company. The final result was a segmented solid model of the maxilla, midface and scull base (figure 2).

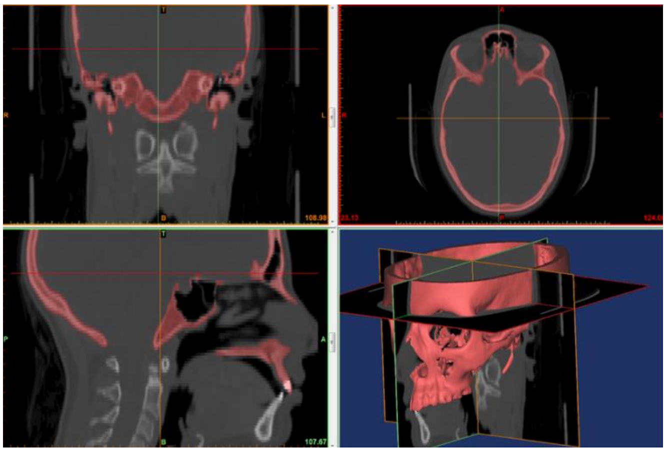

Figure 2: Segmentation of dicom data

The difference in bone geometry and structure can be represented in a cut in the Le-Fort-I plan, a midfacial plan above the root of the teeth from the cavum nasi straight to the basal pterygoid bone. In figure 3 a cut on the Le-Fort-I plane shows a lot of differences of bone structure on the both sides of the midface. The distribution of the bone structures is quit asymmetric. That means also differences and asymmetries in biomechanical response in case of symmetric bone cut and load.

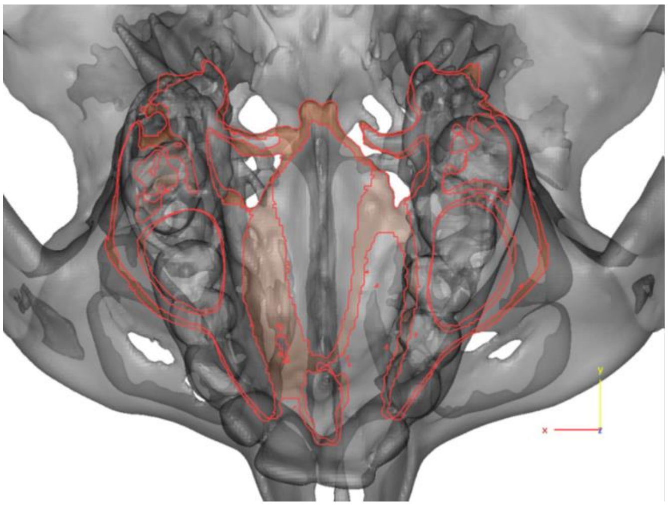

Figure 3: Asymmetric bone structure in the Le-Fort-I plane

In the next step we inserted fix defined cuts into the segmented model. The scientific literature described a lot of types of osteotomy and modifications. But the indications and the extension of individual osteotomy are not clearly defined. So the disconnecting of the midpalatal suture and the pterygo-maxillary junction is largely fixing.

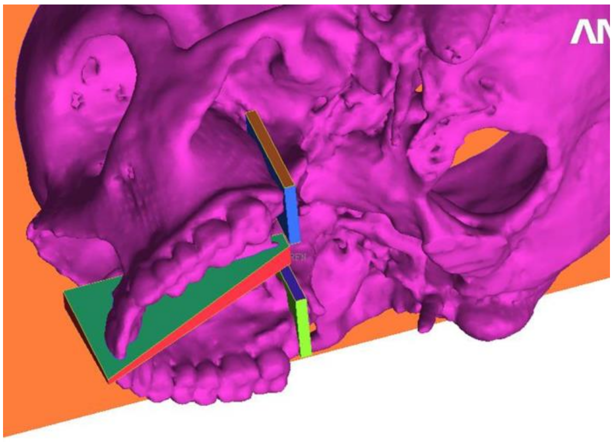

Figure 4: Fix lines of osteotomy

The osteotomy of the lateral sinus wall is not need in every single case and in full extension. So the extension differs and is determined by the kind of osteotomy. In these areas along the Le-Fort-I plane we defined two cutting areas on each side. We defined an individual start point and an end point on the model of each line of osteotomy. A FEA analysis with Ansys® 14.0 simulates the distraction. For the biomechanical constants we take standard values. The values for reaction forces and fragment moving as well as start points and end points of the lines of osteotomy are input parameters for the optimization routine with optiSLang® v3.

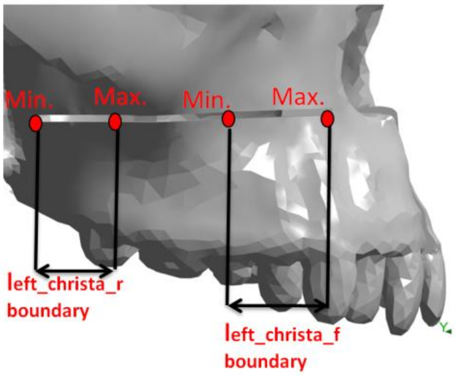

Figure 5: Individual model based cutting area on right Le-Fort-I plane

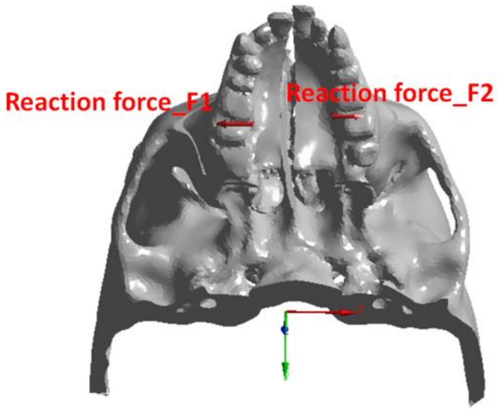

Figure 6: Reaction forces on the maxilla model

As objectives we defined a maximum of symmetry, a minimum of reaction forces and a minimum of the cutting length. The optiSLang® output fixes these parameters und Ansys® software generates new start values for the cutting areas on the both sides. So a new iteration starts.

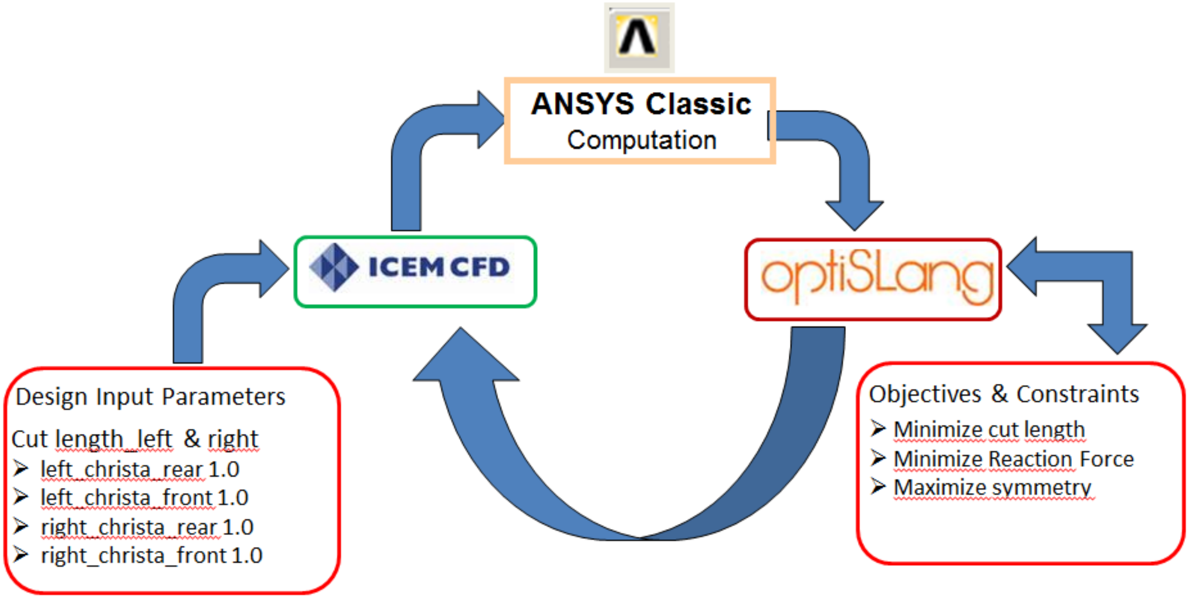

Figure 7: Optimization workflow

Routinely we do about 150 cycles for iteration and pick out these cases with optimal objective parameters.

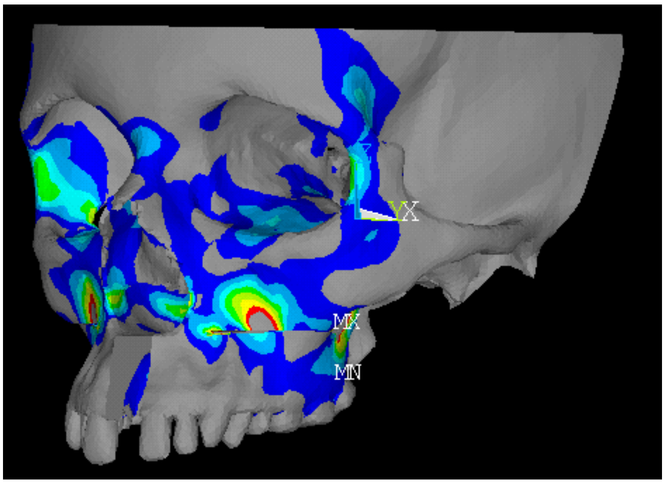

Figure 8: Finite element analysis of the model after insertion of the fix and individual model based bone cuts

The decision to use a specific result for the operative procedure, the surgeon applies exclusively. He makes his decision based on his knowledge, skills and experience. Thus, the preoperative analytical workflow serves biomechanically possible cuts on the bone with the greatest possible symmetry, small reaction forces and minimal osteotomy.

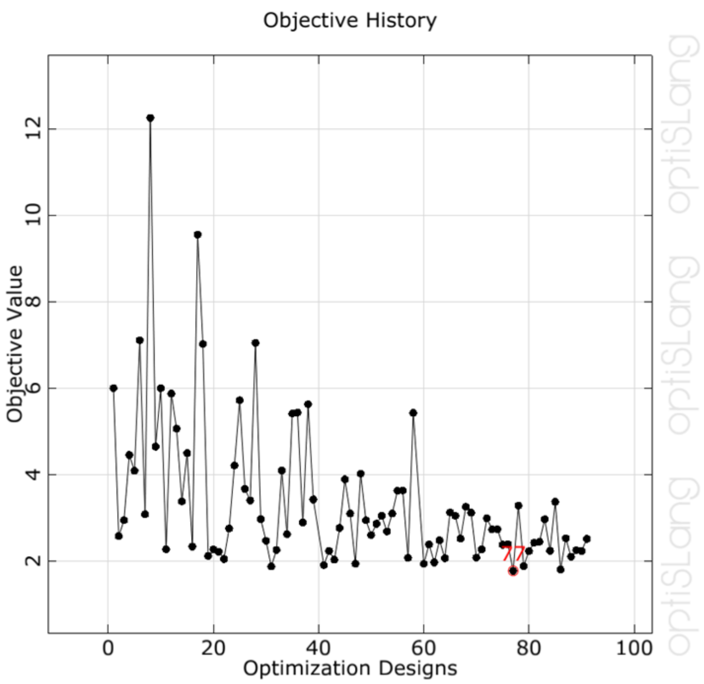

Figure 9: Optimization process with iteration and objective values

We transferred the data to an individual template that represents a cutting guide for intraoperative use.

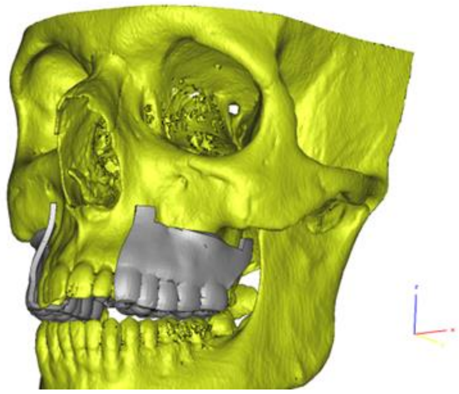

Figure 10: Cutting guide

3 Results

The distribution of the von Mises stresses depends on the anatomical geometry. Higher von Mises stress results from greater expansion values. The results indicate a parallel maxilla widening in transversal direction. Generally high stress levels were observed under the basal plates of distractor. Because of limited elasticity of sphenoid region and complex anatomical geometry high stress level occurs with potentially risk to interferes vascular and neural structures. Low stress level was recognized in dental-alveolar bone. After osteotomy we found an extreme parallel distraction (figure 11).

Figure 11: Distraction, after 14 days

Four weeks after surgery we did a photogrammetric measurement. The mirroring of the face demonstrates almost parallel face. Differences may be due to changes such as hematoma of the soft tissues (figure 12). The exact parallel distraction of the maxilla is an optimal prerequisite for additionally orthodontic or orthognathic treatment.

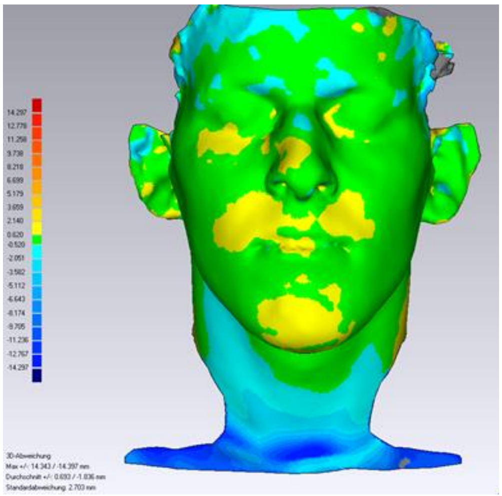

Figure 12: Comparison of symmetry, 4 weeks after distraction

The exact parallel distraction of the maxilla is an optimal prerequisite for additionally orthodontic or orthognathic treatment.

4 Discussion

Standardization in surgical work is important to verify the high quality. Focus on patient's interest, standardization should improve comfort and compliance. Shorter surgical intervention time and better wound healing with reduction of negative side effects are the basis therefore. Minimal invasive surgery under respect of individual anatomical situation is an important way. To evaluate and control stress, strain and forces the FEA with three dimensional analyses of patient's data is valid (Provatidis et al. 2006, Gautam et al. 2007, Provatidis et al. 2007, Boryor et al 2008). Two dimensional methods for evaluation should be replaced by 3D methods. So the future can clear define indication, limitations and contraindications for 3D FEA with optimization strategy.

5 Conclusion

With 3D analyzing of CT data there is a valid possibility to recognize individual stress distributions in SARME patients using bone anchored distraction device. Extent of osteotomy is individual and depends on stress level of connecting bone structures and the distraction distance. Analyzing the CT data prior the surgical intervention can help to perform the maxillary bone split in an optimal way with respect to individual anatomic conditions. The finite element model with optimization strategy therefore represents an individual simulation model to evaluate stress and force distribution in maxillary bone structures with optimal conditions for patient specific results.

6 References

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