Prediction of Cranio-Maxillofacial Surgical Planning Using an Inverse Soft Tissue Modelling Approach

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Abstract. In cranio-maxillofacial surgery, the determination of a proper surgical plan is an important step to attain a desired aesthetic facial profile and a complete denture closure. In the present paper, we propose an efficient modeling approach to predict the surgical planning on the basis of the desired facial appearance and optimal occlusion. To evaluate the proposed planning approach, the predicted osteotomy plan of six clinical cases that underwent CMF surgery were compared to the real clinical plan. Thereafter, simulated soft-tissue outcomes were compared using the predicted and real clinical plan. This preliminary retrospective comparison of both osteotomy planning and facial outlook shows a good agreement and thereby demonstrates the potential application of the proposed approach in cranio-maxillofacial surgical planning prediction.

Keywords: surgical planning prediction, soft-tissue simulation, mass-tensor modeling, cranio-maxillofacial surgery.
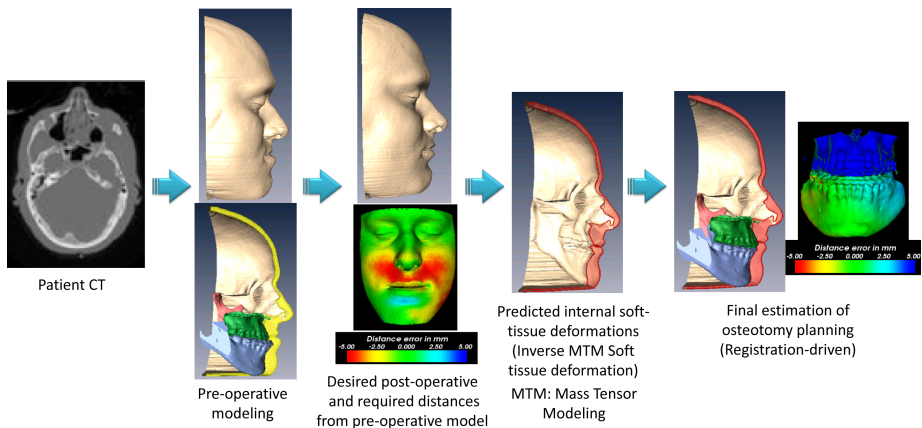
1 Introduction

Soft tissue simulation approaches are used in CMF surgery to predict the post-operative facial appearance of patients undergoing orthognathic surgeries. Besides functional improvements (chewing, swallowing, breathing etc.), the aesthetic enhancement is of major concern in affected patients, as they want to know before surgery how they will look like post-operatively. The current simulation approaches for soft tissue deformations following CMF surgery show good results in terms of accuracy and compliance to the clinical workflow [1-3]. In these approaches, the goal is to use a biomechanical model to predict how the patient's facial soft tissues will deform given an osteotomic surgical plan. The simulation is then capable of providing the surgeon with a post-operative scenario, from which adaptations or changes to the surgical plan can be performed in order to prepare the patient for the changes in his/her appearance. An alternative way would be the virtual creation of a facial outlook according to the desires of the patient and surgeon recommendations, from

which the surgical plan could be derived. In this paper we present an approach to predict the surgical plan necessary to attain a desired post-operative patient's facial outcome and an optimal occlusion between mandibular sections. The method features an inverse modeling paradigm used to predict the displacement of bony structures from the desired post-operative outcome. We present preliminary results on six patient cases undergoing different types of orthognathic surgery, demonstrating the ability of the method to predict the surgical plan needed to attain the post-operative scenario.

2   Method

In this section the workflow for the surgical plan prediction is presented. An overview of the proposed pipeline is presented in **Fig. 1**. First, the pre-operative tissue model and information (i.e. typical osteotomy segments, muscle prediction, and mechanical information) are built from the pre-operative CT scan, as proposed in [3]. Based on this model, the desired post-operative outlook can then be derived by means of a Computer Aided Design (CAD) tool that allows the surgeon to deform the pre-operative model. We use the resulting surface-to-surface displacement as boundary condition of a biomechanical model [3], which allows us to compute the deformation of the internal soft tissues in contact with the bone segments (called hereafter inverse soft tissue deformation). In the last step, an iterative surface-to-surface rigid registration with occlusion (denture equilibration) and collision constraints is used to compute the final predicted planning by registering the bony segments to the internal soft tissues. Below, we explain in more detail the inverse soft tissue deformation and final estimation of the osteotomy plan.

Patient CT

Pre-operative modeling

Desired post-operative and required distances from pre-operative model

Predicted internal soft-tissue deformations (Inverse MTM Soft tissue deformation)
MTM: Mass Tensor Modeling

Final estimation of osteotomy planning (Registration-driven)

Fig. 1. Illustration of the proposed concept for patient-specific CMF surgical plan prediction. The required displacement boundary conditions over the pre-operative skin surface are obtained based on the comparison with the desired facial outlook. Using MTM modeling, the deformations of internal soft tissues are computed, from which the final estimation of the planning is obtained from an occlusion-constrained registration-driven approach.

2.1   Soft Tissue Simulation

Pre-operative Tissue and Bone Modeling

Following the approach presented in [3], we derive from the pre-operative CT scan, a pre-operative model of the patient that includes soft tissues (external and internal), bone tissues (skull, maxilla, and mandible), and predicted facial muscles. Osteotomy segments are derived from the surgeon, and mechanical information (material properties and boundary conditions) is set following [3, 4]. As an example, **Fig. 4** shows the pre-operative models of six patients that underwent CMF surgery. Note that for visualization purposes the predicted facial muscles are not visualized, but used in the simulations.

Boundary Conditions for Inverse Soft Tissue Modeling

From the pre-operative model, the desired outlook can be generated by means of CAD software, or any other surface deformation based approach that enables "sculpturing" of the pre-operative model. The resulting displacements starting from the pre-operative to the desired outlook model are regarded as displacement boundary conditions (see **Fig. 2**a). This information enables the connection between the desired outlook, the biomechanically driven estimation of internal soft tissue deformations and the final prediction of the surgical plan. In addition, as proposed in [3], sliding contact is defined on the teeth area in order to improve the simulation accuracy in the error-sensitive region (see **Fig. 2**b). The most posterior plane of the volumetric soft-tissue model is assumed fixed (**Fig. 2**c). The remaining points are considered free to move.
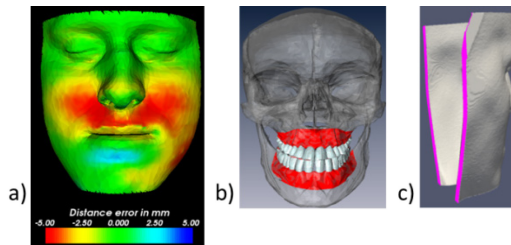
Fig. 2. Three types of boundary conditions defined on the patient model a) surface skin displacement b) sliding sections illustrated with different colours c) fixed points

### Biomechanical Simulation Using Mass Tensor Modeling (MTM)

In order to compute the deformation of internal soft tissues in contact with the bone segments, we used the defined boundary conditions and Mass Tensor Modeling (MTM) simulation [3, 4]. By using MTM in a reverse way, we are able to derive deformations of the internal soft tissues. As facial soft tissues follow an elastic behavior, we are able to seemingly invert boundary conditions of the simulation so to derive bone segment displacements from the displacements of the external soft tissues.

2.2   Osteotomy Planning Prediction by Constrained Surface Registration

In the last step, the final planning is derived by surface-to-surface registration. Since surface points in the deformed internal soft tissue are in contact with maxilla and mandible segments, we use an Iterative Closest Point (ICP) based registration method to recover the displacements of the bone segments. In order to consider proper occlusion for denture equilibration and collision for realistic surface matching, we extended the constrained ICP approach presented in [5] to consider deviations from a perfect occlusion as well as collision amongst maxilla, mandible, and internal soft tissues. We modeled occlusion by measuring the misalignment between the maxilla and mandibular dental arches through manually selecting anatomically corresponding points (at least three) on each arc (e.g. tip of the vestibular cuspid on the first upper premolar and contact point on first and second lower premolar), as proposed in [6]. The registration process then aims at minimizing the surface distance errors e^{upper}, e^{lower}, and e^{arch}, for maxilla, mandible, and denture arches, respectively, with penalizations $W_x^{(\cdot)} = \gamma^{(\cdot)} \| e_x^{(\cdot)} \|$ if point x infringes collision, and $W_x^{(\cdot)} = 1$, otherwise. Weights $\gamma^{(\cdot)}$ are set to weigh the amount of collision penalization and are set empirically [5]. Weights α and β are used to weigh the balance between occlusion and desired outlook. Collision is computed as in [5].

$$argmin \; \alpha \left(\sum_i W_i^{upper} \| e_i^{upper} \|^2 + \sum_j W_j^{lower} \| e_j^{lower} \|^2 \right) + \beta \sum_k W_k^{arch} \| e_k^{arch} \|^2 \qquad (1)$$

To find the set of rigid transformations for the bone segments that minimize (1), we used alternating optimization heuristics considering the desired outlook components and occlusion. As example, **Fig. 3** (a-c) shows the displacement of bone segments for case number five. See **Fig. 3** (d) as example of recovered occlusion.
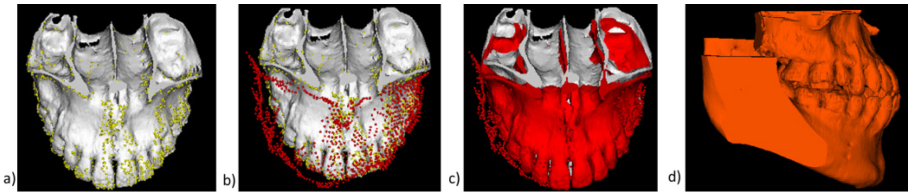
Fig. 3. Example of bone segment displacements obtained using the constrained ICP registration. Yellow points (a) are the pre-operative tissue points in the vicinity of the bone surface. Red points in (b) are the deformed internal tissue points after inverse soft tissue modeling. White and red bone segments in (c) correspond to the pre-operative and final predicted segments, respectively. (d) An example of recovered occlusion in patient no. 5.

3   Results

3.1   Clinical Data and Evaluation Procedure

To evaluate the proposed approach six patient datasets that underwent different types of CMF surgery were analyzed retrospectively. For each case, pre- and post-operative CT scans were available as well as the surgical plan.

In order to evaluate the ability of the method to predict the surgical plan based on a given facial outcome, we took advantage of the retrospective data and considered the real post-operative outlook as the desired outlook, and the actual surgical plan as ground truth. For each case, occlusion and compliance to the desired outlook was set equally (i.e. $\alpha = \beta = 0.5$ in Eq. (1)).

For each case, pre-operative models were created and osteotomy segments reproduced based on the type of CMF surgery chosen by the surgeon [3]. **Fig. 4** shows for each case the pre-, and post-operative bone segments (white and green, respectively) as well as the pre-operative patient face.
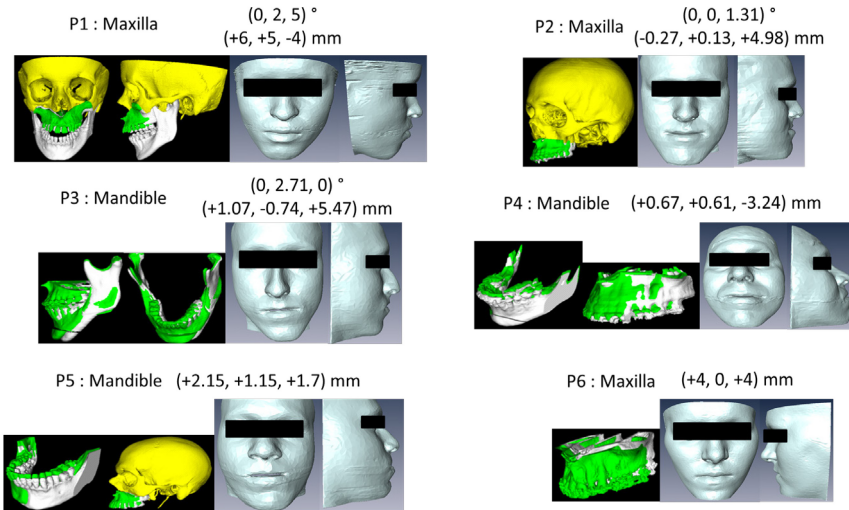

Fig. 4. Osteotomy segments for the six clinical cases that underwent different types of CMF surgery. For each case pre- and post-operative situations are displayed in white and green, respectively. The pre-operative patient face is shown next to the surgical plan. The amount of rotation (axial, sagittal, coronal) and translation (horizontal, vertical, anterior-posterior) are presented on top for the respective segment.

3.2   Comparison of Predicted and Actual CMF Surgical Plan

In order to assess the accuracy of the proposed method, the predicted segments for each patient were compared with the respective actual post-operative segments. For each patient the pre-operative, predicted, and actual post-operative osteotomy segment are shown with white, orange and green color in **Fig. 5**, respectively. Using the

protocol described in [3], distance measurements between corresponding points of the predicted and the actual post-operative segments were quantified and are shown as color-coded images on the rightmost column in **Fig. 5**. The predicted segments present a good similarity to the actual post-operative segments except for case number five, where despite of the agreement in rotation for the mandible segment, the inverse modelling predicted a different advancement of mandible, which was found to be due to the occlusion constraints. After inspection of the post-operative segments and discussion with the surgeon, the proposed predicted planning was regarded as an improvement over the actual executed plan as shown in **Fig. 3** (d). Complete processing time was below 10 mins on each case compared to hours needed for the current clinical workflow.
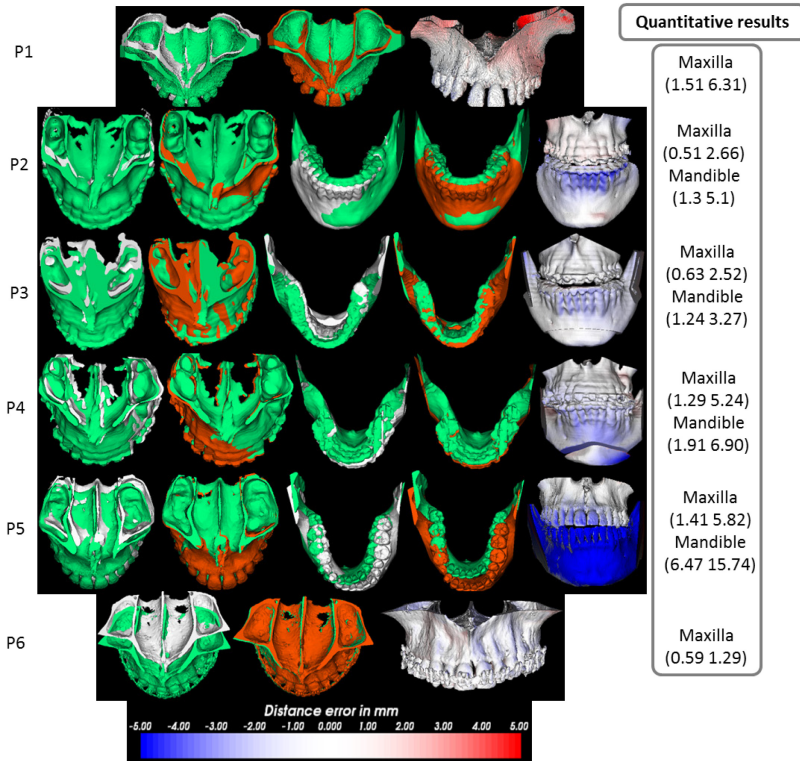
Fig. 5. Predicted (orange color), actual post-operative (green color), and pre-operative segments (white color) for the respective patients. The quantitative results (distance errors) from the post-operative segments are shown as color-coded images on the predicted model on the rightmost column with the (median maximum) error values in mm indicated for the respective segments. The blue color means the proposed approach falls posteriorly than the real post-operative segment.

3.3   Soft Tissue Prediction

As an additional evaluation, simulated soft-tissue outcomes were compared using the predicted and real clinical plan. We remark that in this case the real post-operative outcome was not used for comparison in order to remove from the evaluation the implicit error of the MTM simulation, which can favorably compensate for errors in the predicted surgical plan or add error to the evaluation of the surgical plan prediction. Distance measurements between corresponding points of the simulated and the post-operative surface skin were quantified based on the method presented in [3], and are displayed for all cases in **Fig. 6** using a color-coded map, where the red color means the simulated skin surface falls posteriorly to the post-operative surface mesh, and blue indicates that the simulation lies anteriorly to the post-operative skin surface. The white color is associated with the range [-2,2] mm, the clinically accepted range where simulation errors are not recognizable by the human eye [7]. The facial simulation results using the predicted and actual planed approach are in close agreement, except for case number five where the predicted plan for the mandible section is different from the actual one due to the ability of the approach to propose a better occlusion.
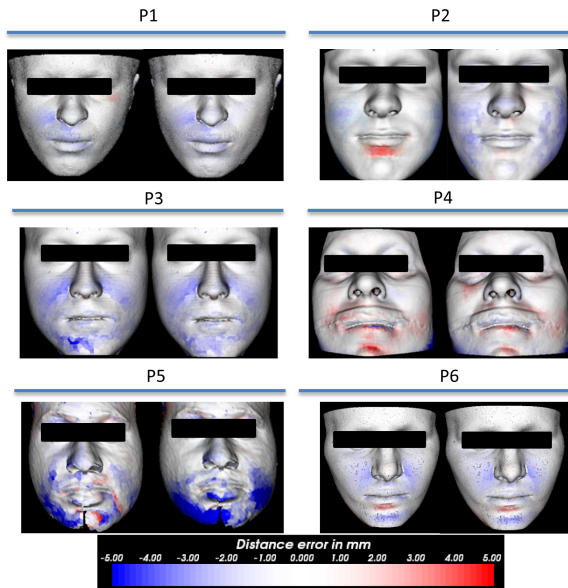
Fig. 6. Color-map comparison of distance errors between simulation results using the predicted (left column) and actual (right column) osteotomy planning in six patients. Please note that the red colour indicates posterior position of simulation compared to the post-operative.

4   Conclusion

In this paper we have presented an approach to predict a CMF surgical plan based on the desired post-operative facial outlook. The proposed approach employs a fast

biomechanical model to derive from the desired facial outlook, the deformation of internal soft tissues, which is followed by constrained surface registration between bone segments and internal soft tissues. The proposed registration component considers collision and occlusion constraints, and its formulation allows us to derive in a straightforward manner different levels of interplay between quality of occlusion and compliance to the desired outlook (i.e. constraints relaxation). Furthermore, and in regards to a biomechanical simulation that would model the entire ensemble of bone and soft tissues, the proposed approach avoids known issues of layer detachment and convergence related to the high elasticity transition present at the interface of bone and soft tissue materials. Preliminary results on a prospective set of clinical cases showed in five out of six cases a high level of agreement to the actual surgical plan, and one case where the proposed approach was confirmed to improve the actual executed plan. Our method differs in concept with reference [3] and is like an inverse simulation accounting for optimal occlusion and non-collision and desired facial outlook. The desired outlook can be easily defined by the surgeon using a CAD software [8]. In the presented paper, we did not use any CAD system, instead and for validation purposes, we considered the post-operative profile as the desired outlook.

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