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Accuracy Improvement In Cranio-Maxillofacial Soft Tissue Simulation Using A Muscle Embedded Meshing Approach

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***Abstract*—In the presented paper, we propose to improve the state-of-the-art approach for Cranio-Maxillofacial (CMF) soft tissue simulation by considering a new image-based meshing approach that accurately models the interface between different tissue types. The proposed approach has been initially evaluated on soft tissue deformations of four patients undergoing CMF surgery using post-operative CT scans. The results indicate improved prediction and robustness of the surgical planning outcome when compared to the state-of-the-art method while decreasing the simulation time.**

I. Introduction

Cranio-Maxillofacial (CMF) surgery deals with the treatment of abnormal facial disfigurements. One of the most demanding issues in this field is to accurately predict facial outcomes based on the surgical planning. This area of research has progressed significantly since the incorporation of computer assisted approaches tailored for soft tissue simulation. Currently, the state-of-the-art soft tissue simulation [1] has significantly improved the simulation accuracy, yet maintained clinical usability, by introducing facial muscle modelling and its anisotropic properties as well as buccal sliding conditions (coupling between hard and soft tissue) in the CMF simulation pipeline.

A limitation of this state-of-the-art modelling approach is the difficulty in determining muscle intersections with tissue elements in order to assign muscle-tissue properties, accordingly. The equivalent material property is then calculated by considering the volumetric proportion of muscle in each tetrahedron using a sampling approach [2]. As shown in Fig.1, random points (black dots) are generated inside each element (tetrahedron) and geometrical tests described by the arrows allow us to find approximate volumetric proportions, which are then used to weight material properties in each element. Such approach leads to a suboptimal material property assignment, similarly to the partial volume effect in medical imaging where a voxel's intensity results from the contributions of different tissue types.

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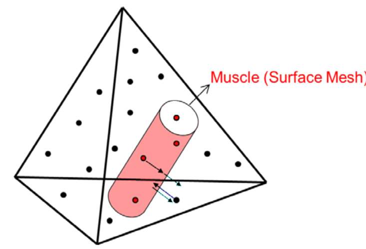

Figure 1. *The muscle portion in the sate-of-the-art modelling is obtained based on the sampling method where random points are generated inside the tissue element to calculate the muscle portion within the tissue.*

We propose to replace this sampling method with a single-step meshing approach that precisely models the interface between different tissue types, hence improving the accuracy of the simulations. In order to quantify the gain in simulation accuracy, the surgical outcome of four patients undergoing CMF treatment were simulated and compared to the results using the state-of-the-art method.

II. Muscle embedded tissue Image and mesh

Facial soft tissue simulation requires the patient's facial (extra-cranial) tissue to be reconstructed from the CT imaging data (shown in yellow in Fig.2a). This region in the state-of-the-art modelling is segmented manually and a volumetric mesh is then created using a standard tetrahedral mesh generator available in the external softwares. Then, muscle segments (red in Fig.2a) are estimated using a facial muscle atlas transformed to the patient's face using thin-plate spline (TPS) [3] deformation model. Finally, the sampling approach, described in the previous section, is employed to calculate the muscle percentage inside the tissue element. Thus, the facial tissue is initially constructed alone, onto which the muscles are augmented in the latter stage. In this paper, to overcome the speed and modelling accuracy limitations of this two-step approach, we propose a single-step generation of volumetric facial models with embedded muscles.

In contrast to the previous meshing approach, the data (facial tissue and muscle segments) are transformed into the image domain using specific functions from Matlab. To this end, a boolean difference operation between the skull, and the skin surface generated with a simple threshold, was applied to obtain the region residing between the skin and skull. The resulting extra-cranial tissue section was transferred into the image domain with a constant scalar given to the tissue region (yellow in Fig 2b). Muscle segments were added afterwards into the tissue image using a different scalar value than surrounding tissue. CGAL (Computational

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Geometry Algorithms Library) [4] was then employed to generate the volumetric mesh from this tissue-muscle image (see Fig.2c). The resulting volumetric mesh then has elements residing solely in either inside or outside the muscles, with element interfaces delineating the muscle surfaces as required. Thus, the sampling approach is no more needed and each element is assigned its corresponding tissue properties.

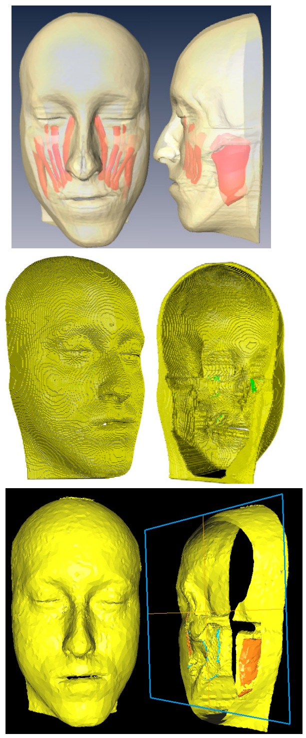

Figure 2. *The meshing process in the proposed approach exemplified in one patient. a) the facial (extra-cranial) tissue and the relevant muscle segments for CMF surgery (orbicularis Oculi, levator labii superioris alaeque nasi, levator labii superioris, masseter, zygomaticus major and zygomaticus minor) b) the image of the facial tissue plus the muscle segments presenting a different scalar value than the surrounding tissue c) the volumetric mesh generated using CGAL [4]. The muscle volumes are visible in the cut section.*

Anisotropy is an essential mechanical feature of muscles. In order to assign anisotropy parameters accordingly, we had to identify the orientation of each facial muscle, for which we used Oriented Bounding Boxes (OBBs) [5]. The longer axis of each bounding box was regarded as the fiber orientation of each muscle segment.

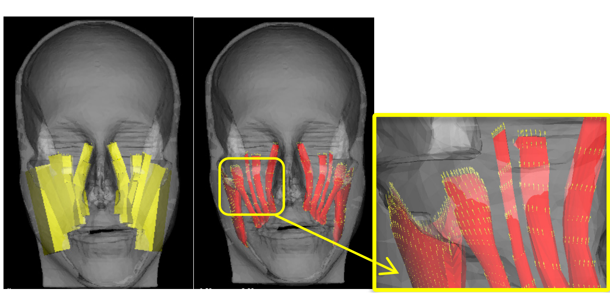

Figure 3. *Oriented Bounding boxes (OBB) were used to obtain the muscles direction. The masseter muscle was represented by a single OBB, while the other muscles were represented by two-level OBBs.*

III. Soft Tissue Simulation

Once the volumetric mesh was obtained for a patient following the procedure stated in section II, the material properties were defined and assigned to the tetrahedral elements. In this study, a linear elastic behaviour was assumed for facial tissues. Material properties of facial soft-tissue (i.e. the Young's modulus of muscle tissue along and across fibers) and the fat within tissues were adopted from [6] (see Table I).

TABLE I. Material properties used for simulation.

	Young's modulus (MPA)	*Poisson Ratio*
Fat	0.003	0.46
Muscle across fiber	0.79	0.43
Muscle along fiber	0.5	0.43

Regarding boundary conditions, a sliding contact surface was defined on the teeth area in order to improve the simulation accuracy in the error-sensitive region (see Fig.4a). In the buccal region (red in Fig.4b), the bone displacements were projected directly on the surrounding tissue points assuming that these displace the same amount as the neighbouring bones. The most posterior plane of the volumetric soft-tissue model was assumed to be spatially fixed (Fig.4c). The remaining points are considered free.

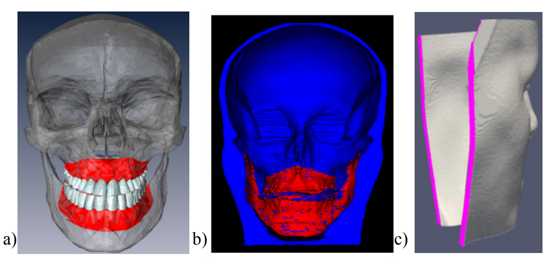

Figure 4. Three types of boundary conditions defined on the patient model a) sliding-contact segment b) joint setions c) fixed points.

Similarly to the approach of Kim et al. [1], numerical simulations were performed using transversely-isotropic Mass Tensor Model (MTM).

IV. Clinical Data

To evaluate the proposed approach, four patients undergoing CMF surgery were modeled and post-operative soft tissue deformations of patient's faces were simulated and compared with their corresponding post-operative faces obtained from CT scan. The osteotomy planning for these patients were provided by the maxillofacial research center of Basel University. The respective advancement or setbacks of maxillary and mandibular parts are qualitatively presented in Fig. 5, in which the initial and planned segment positions are indicated in white and green, respectively. The planned surgical interventions are presented in Table II.

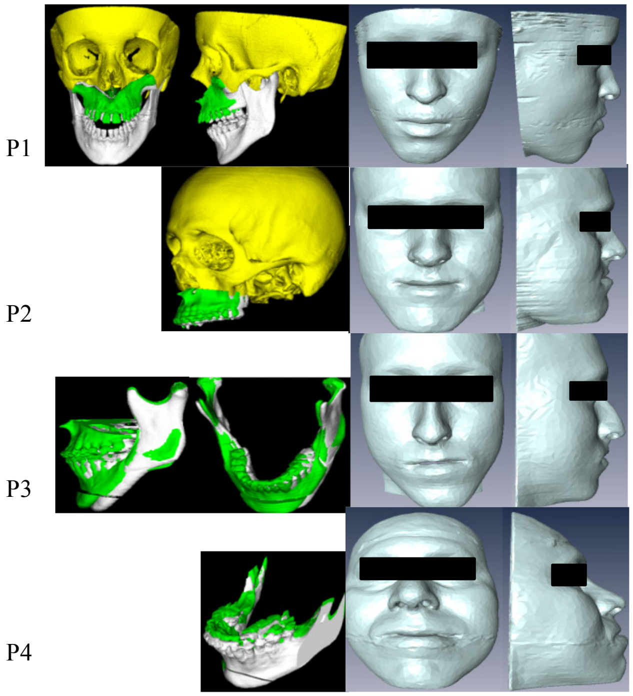

Figure 5. *Osteotomy planning for the selected patients undergoing different types of CMF surgery. On each case pre- and post-operative situations are displayed in white and green, respectively. The pre-operative patient face is shown next to the surgical planning.*

TABLE II. SURGICAL PROCEDURES PERFORMED ON THE PATIENT CASES

Patient Number	Planning details		
	Deformed Section	*Translation [mm] (horizontal, vertical, anterior-posterior)*	*Rotation*
1	Maxilla	(+6, +5, -4)	(0°, 2°, 5°)
2	Maxilla	(-0.27, +0.13, +4.98)	(0°, 0°, 1.31°)
3	Mandible	(+1.07, -0.74, +5.47)	(0°, 2.71°, 0°)
4	Mandible	(+0.67, +0.61, -3.24)	-

V. VALIDATION WITH POST-OPERATIVE CT SCAN DATA

In order to assess the accuracy of the new strategy, a retrospective validation of four clinical cases with the post-operative scans was performed. Post-operative CT scans of the patients were used as ground truth to assess the simulation accuracy on each patient. The amount of displacement was determined by registering the pre-operative and post-operative surface meshes using the Iterative Closest Point (ICP) algorithm [7]. Distance measurements between corresponding points of predicted and actual post-operative facial skin surface were computed based on the closest matching points and are shown as colour-coded distance map for all patients in Fig.6. Red means the simulated skin surface falls posteriorly to the postoperative surface mesh, while blue indicates that the simulation lies more anteriorly. White marks the acceptable range of [-2,2] mm, where simulation errors are not visible to the human eye [8].

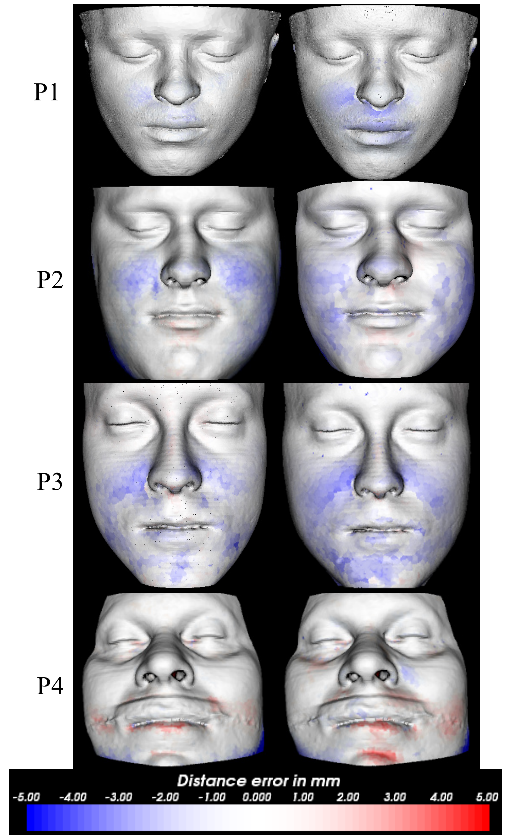

Figure 6. *Color-map comparison of distance errors between simulation results and post-operative image in four patients using the proposed (left column) and a state-of-the-art (right column) modelling approaches.*

The distributions of surface errors for the proposed method with muscle-compliant meshing and the previous method with post-sampled mechanical property assignment are plotted in Fig.7. As seen, the proposed method results in – although not substantial– yet a consistent improvement.

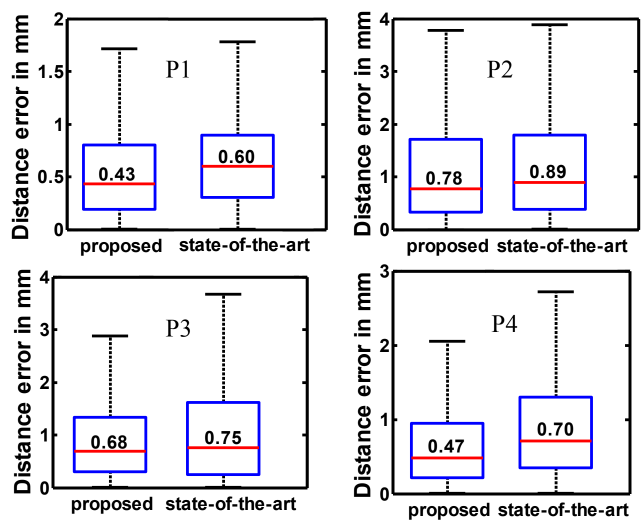

Figure 7. Box-Plot of simulation results for the proposed (left column) and state-of-the-art (right column) models quantified in the selected patients. The Median for both approaches are shown on the respective boxes.

In order to quantify overall simulation accuracy, cumulative errors were calculated for all patients and for both modelling approaches (see Fig.8). In Fig.8, the red and blue lines denote the proposed and the state-of-the-art approaches, respectively. In each figure, the percentage of distance errors below 1 mm and 2 mm are marked. Although the improvements again vary such as minor for P2 but significant for P4, there is still a consistent improvement by using the proposed meshing technique in all tested cases. In addition to the improvement in the simulation accuracy, the proposed method is faster in terms of meshing and material properties assignment as the averaging aspect (about 3-5 mins) is neglected. The meshing approach is indeed much more robust than the previous method. In the latter, the tetrahedral meshing was limited by the presence of element intersection, mis-orientations in the surface mesh.

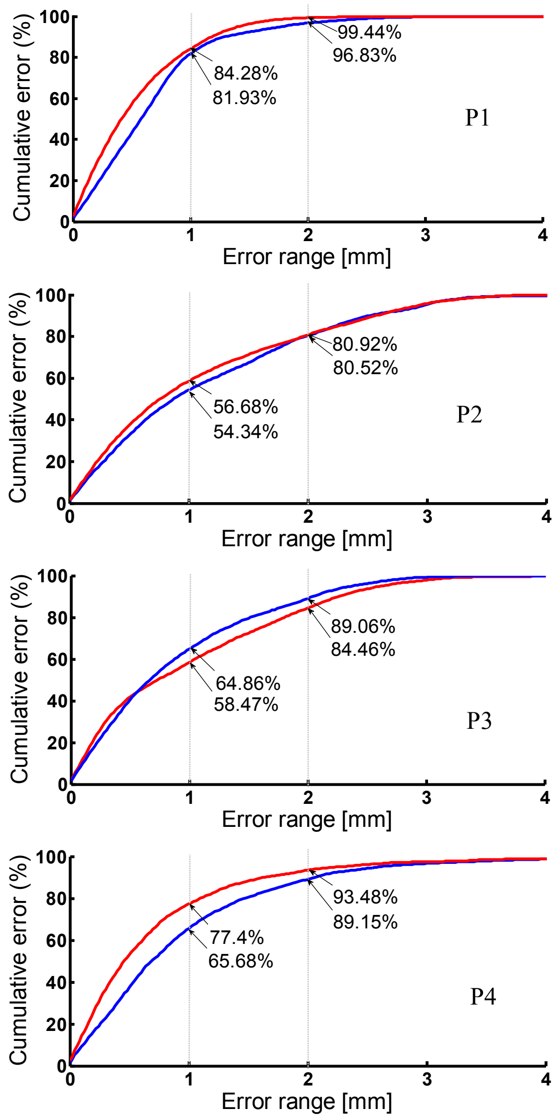

Figure 8. Cumulative simulation errors over the four clinical cases. The proposed approach and the state-of-the-art are shown with red and blue colours, respectively.

VI. Conclusion

A muscle-compliant meshing technique has been tested for CMF soft tissue simulations following the hypothesis that models abiding tissue interfaces may lead to higher simulation accuracy. A retrospective validation study with real postoperative CT scans confirmed that the proposed approach for the tissue-muscle meshing is faster and more robust and indeed yields a better prediction of postoperative facial look. In the proposed method, as novel characteristics, the averaging aspect is neglected and the volumetric mesh is obtained in one step using a muscle-embedded image based meshing which results in a more accurate material property assignment and indeed higher outcome simulation accuracy.

Acknowledgment

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