Fast Soft-Tissue Simulation Method for Cranio-Maxillofacial Surgery Using Facial Muscle Template Models

Purpose

There have been increasing demands for predicting post-operative soft-tissue changes in computer-assisted cranio-maxillofacial (CMF) planning. Some commercial solutions have been developed for simulating post-operative soft-tissue variations, but most of them fail to realize delicate soft-tissue variations around lips and nose areas, which are error-sensitive regions for surgeons. Such subtle changes can be realized with complicated simulation methods based on finite-element model (FEM). However, they require laborious mesh preparation and huge computational expenses, which hinder these solutions to be used in clinical practice. We propose a computationally efficient and bio-mechanically relevant soft-tissue simulation method driven by predicted facial muscles using template models. The proposed method can be seamlessly integrated into the clinical workflow without requiring additional imaging modality, such as Magnetic Resonance Imaging (MRI).

Methods

Manual segmentation with commercial software (Amira, Mercury Computer Systems) was performed on conventional Computed Tomography (CT) scans, followed by automatized tetrahedral mesh generation using the same software. Patient-specific facial muscles were constructed by morphing the muscles from a facial template model as shown in Fig.1a, since it is almost impossible to identify individual muscles in clinical CT. The morphing procedure was executed using a thin-plate-spline (TPS) algorithm based on 32 skull anatomical landmarks. Oriented-bounding box (OBB) was used to obtain the principal direction of individual muscle as shown in Fig.1b.

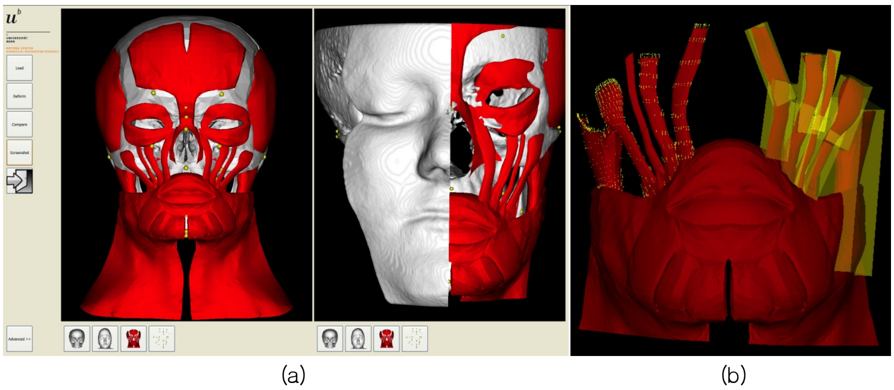

Fig. 1: (a) Morphing of facial muscles from template model to patient-specific model, (b) Extraction of muscle direction using oriented-bounding boxes.

Corresponding material properties were assigned by considering the geometric features of facial muscles, such as intersecting proportion and direction of the muscle in each tetrahedron. Soft-tissue simulations were performed using mass-tensor model (MTM) with consideration of transversely isotropy of muscles. Commercial FEM software (Abaqus/CAE 6.7, Dassault Systems) was used for coarse estimation of simulation accuracy and computational performance. Homogeneous material model was assumed for this comparison study.

Retrospective validation with post-operative CT scan of the patient, who had been operated due to craniofacial deformity called Pfeiffer-Syndrom, was followed as for true accuracy validation. Two different muscle template models were introduced to observe the sensitivity of template muscle models in simulation results. One is more generic model developed for educational purposes, the other is patient-specific model segmented from high-resolution MRI scan. Simulation accuracy was assessed by measuring distance between simulated and post-operative skin surfaces based on closest point search strategy.

Results

Surface to surface distance error between FEM and MTM was only 0.023mm±0.0061mm. The overall computation of MTM was almost 18 times faster than FEM. (MTM: 3.8 sec, FEM: 67 sec). This computational efficiency can be even higher considering successive simulations with different surgical plans, since pre-computation of stiffness tensor can be possible for MTM. This superiority can be also maintained while extending to transversely isotropic MTM.

Post-operative CT scan (Le Fort III osteotomy) was compared with simulation results in different tissue models: homogeneous (Fig.2a), transversely isotropic (Fig.2b,c). As shown in Fig.2, the mean error was decreased by incorporating transversely isotropy of muscles. Statistical analysis using Wilcoxon rank sum test ($p<0.05$) showed that there was statistically significant difference between homogeneous and transversely isotropic simulations. However, no statistically significant difference was detected between two different muscle templates.

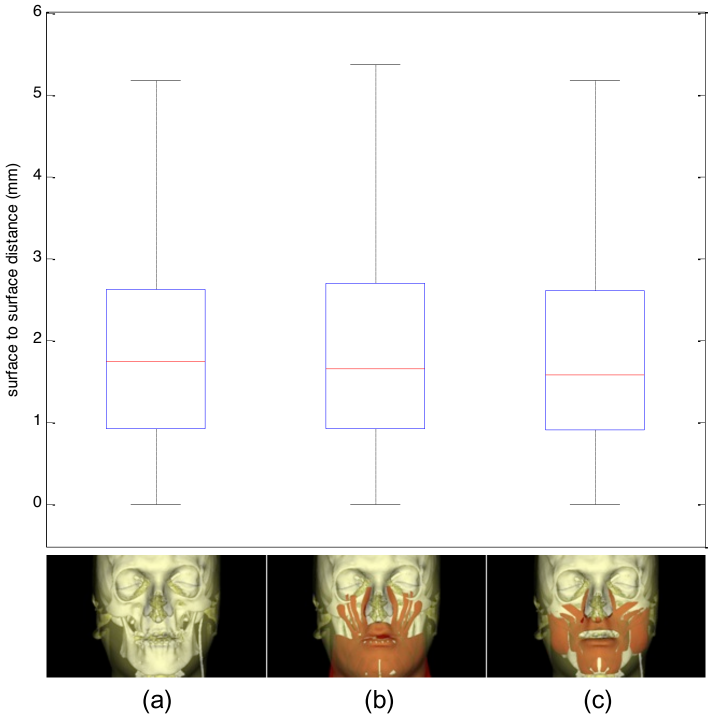

Fig. 2: Comparison of errors between simulations and post-operative result: (a) homogeneous, (b) transversely isotropic using template I, (c) transversely isotropic using template II

Conclusion

MTM computationally outperformed than FEM simulation while maintaining compatible accuracy as FEM. Incorporation of facial muscles using transversely isotropic MTM simulation resulted in statistically meaningful improvements in simulation accuracy with some amount of additional pre-processing works. However, the usage of refined muscle template model did not make statistically significant differences in the evaluated clinical case. Further validation with various clinical cases need to be followed to verify the effectiveness of considering facial muscles in specific surgical procedure.