Two-Stage Simulation Method to Improve Facial Soft Tissue Prediction Accuracy for Orthognathic Surgery

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Abstract. It is clinically important to accurately predict facial soft tissue changes prior to orthognathic surgery. However, the current simulation methods are problematic, especially in clinically critical regions. We developed a two-stage finite element method (FEM) simulation model with realistic tissue sliding effects. In the 1st stage, the facial soft-tissue-change following bone movement was simulated using FEM with a simple sliding effect. In the 2nd stage, the tissue sliding effect was improved by reassigning the bone-soft tissue mapping and boundary condition. Our method has been quantitatively and qualitatively evaluated using 30 patient datasets. The two-stage FEM simulation method showed significant accuracy improvement in the whole face and the critical areas (i.e., lips, nose and chin) in comparison with the traditional FEM method.

1 Introduction

Facial appearance significantly impacts human social life. Orthognathic surgery is a bone-only surgical procedure to treat patients with dentofacial deformity, in which the deformed jaws are cut into pieces and repositioned to a desired position (osteotomy). Currently, only osteotomies can be accurately planned presurgically. Facial soft tissue changes, a direct result from osteotomies, cannot be accurately predicted due to the complex nature of facial anatomy. Traditionally soft tissue simulation is based on bone-to-soft tissue movement ratios, which have been proven inaccurate. Among the published reports, finite element method (FEM) [1] is reported to be the most common, accurate and biomechanically relevant method [1, 2]. Nonetheless, the predicted results are still less than ideal, especially in nose, lips and chin regions, which are extremely

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important for orthognathic surgery. Therefore, there is an urgent clinical need to develop a reliable method of accurately predicting facial changes following osteotomies.

Traditional FEM for facial soft tissue simulation assumes that the FEM mesh nodes move together with the contacting bone surfaces. However, this assumption can lead to significant errors when a large bone movement and occlusion changes are involved. In human anatomy, cheek and lip mucosa are not directly attached to the bone and teeth; they slide over each other. The traditional FEM does not consider this sliding, which we believe is the main reason for inaccurate prediction in the lips and chin.

Implementing the realistic sliding effect into FEM is technically challenging. It requires high computational times and efforts because the sliding mechanism in human mouth is a dynamic interaction between two surfaces. The 2nd challenge is that even if the sliding movement with force constraint is implemented, the simulation results may still be inaccurate, because there is no strict nodal displacement boundary condition applied to the sliding areas. The soft tissues at sliding surfaces follow the buccal surface profile of the bones and teeth. Thus, it is necessary to consider the displacement boundary condition for sliding movement. The 3rd challenge is that the mapping between the bone surface and FEM mesh nodes needs to be reestablished after the bony segments are moved to a desired planned position. This is because the bone and soft tissue relationship is not constant before and after the bone movement, e.g. a setback or advancement surgery may either decrease or increase the soft tissue contacting area to the bones and teeth. This mismatch may lead to the distortion of the resulting mesh. The 4th challenge is that occlusal changes, e.g. from preoperative cross-bite to postoperative Class I (normal) bite, may cause a mesh distortion in the lip region where the upper and lower teeth meet. Therefore, a simulation method with more advanced sliding effects is required to increase the prediction accuracy in critical regions such as the lips and chin.

We solved these technical problems. In this study, we developed a two-stage FEM simulation method. In the first stage, the facial soft tissue changes following the bony movements were simulated with an extended sliding boundary condition to overcome the mesh distortion problem in traditional FEM simulations. The nodal force constraint was applied to simulate the sliding effect of the mucosa. In the second stage, nodal displacement boundary conditions were implemented in the sliding areas to accurately reflect the postoperative bone surface geometry. The corresponding nodal displacement for each node was recalculated after reassigning the mapping between the mesh and bone surface in order to achieve a realistic sliding movement. Finally, our simulation method was evaluated quantitatively and qualitatively using 30 sets of preoperative and postoperative patient computed tomography (CT) datasets.

2 Two-Stage FEM Simulation Algorithm

Our two-stage approach of simulating facial soft tissue changes following the osteotomies is described below in details. In the 1^{st} stage, a patient-specific FEM model with homogeneous linear elastic material property is generated using a FEM template model (Total of 38280 elements and 48593 nodes) [3]. The facial soft tissue changes are predicted using FEM with the simple sliding effect of the mucosa around the teeth and partial maxillary and mandibular regions. Only the parallel nodal force is considered on the corresponding areas. In the 2^{nd} stage, explicit boundary conditions are applied to improve the tissue sliding effect by exactly reflecting the bone surface geometry, thus ultimately improving the prediction accuracy.

2.1 The First Stage of FEM Simulation with Simple Sliding Effect

The patient-specific volume mesh is generated from an anatomically detailed FEM template mesh, which was previously developed from a Visible Female dataset [3]. Both inner and outer surfaces of the template mesh are registered to the patient's skull and facial surfaces respectively using anatomical landmark-based thin-plate splines (TPS) technique. Finally, the total mesh volume is morphed to the patient data by interpolating the surface registration result using TPS again [3].

Although there have been studies investigating optimal tissue properties, the effect of using different linear elastic material properties on the simulation results was negligible [4]. Furthermore, shape deformation patterns are independent of Young's modulus for isotropic material under displacement boundary conditions as long as the loading that causes the deformation is irrelevant for the study. Therefore, in our study, we assign 3000 (Pa) for Young's modulus and 0.47 for Poisson's ratio [4].

Surface nodes of the FEM mesh are divided into the boundary nodes and free nodes (Fig. 1). The displacements of free nodes (*GreenBlue* in Fig. 1b and c) are determined by the displacements of boundary nodes using FEM. Boundary nodes are further divided into static, moving and sliding nodes. The static nodes do not move in the surgery (*red* in Fig. 1). Note that the lower posterior regions of the soft tissue mesh (*orange* in Fig. 1b) are assigned as free nodes in the first stage. This is important because together with the ramus sliding boundary condition, it maintains the soft tissue integrity, flexibility and smoothness in the posterior and inferior mandibular regions when an excessive mandibular advancement or setback occurs.

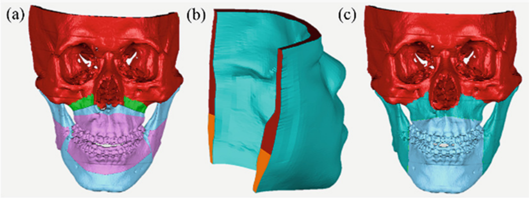

Fig. 1. Mesh nodal boundary condition. (a) Mesh inner surface boundary condition (illustrated on bones for better understanding) for the 1^{st} stage only; (b) Posterior and superior surface boundary condition for both 1^{st} and 2^{nd} stages; (c) Mesh inner surface boundary condition (illustrated on bones for better understanding) for the 2^{nd} stage only. Static nodes: *red*, and *orange* (2nd stage only); Moving nodes: *Blue*; Sliding nodes: *pink*; Free nodes: *GreenBlue*, and *orange* (1st stage only); Scar tissue: *green*.

The moving nodes on the mesh are the ones moving in sync with the bones (blue in Fig. 1a). The corresponding relationships of the vertices of the STL bone segments to the moving nodes of the mesh are determined by a closest point search algorithm. The movement vector (magnitude and the direction) of each bone segment is then applied to the moving nodes as a nodal displacement boundary condition. In addition, the areas where two bone (proximal and distal) segments collide with each other after the surgical movements are excluded from the moving boundary nodes. These are designated as free nodes to further solve the mesh distortion at the mandibular inferior border. Moreover, scar tissue is considered as a moving boundary (green in Fig. 1a). This is because the soft tissues in these regions are degloved intraoperatively, causing scars postoperatively, which subsequently affects the facial soft tissue geometry. The scar tissue is added onto the corresponding moving nodes by shifting them an additional 2 mm in anterior direction as the displacement boundary condition.

In the first stage, the sliding boundary conditions are applied to the sliding nodes (*pink* in Fig. 1a) of the mouth, including the cheek, lips, and extended to the mesh inner surface corresponding to a partial maxilla and mandible (including partial ramus). The sliding boundary conditions in mucosa area are adopted from [2].

Movement of the free nodes (Fig. 1b) is determined by FEM with the aforementioned boundary conditions (Fig. 1a and b). An iterative FEM solving algorithm is developed to calculate the movement of the free nodes and to solve the global FEM equation: $K\delta = f$, where K is a global stiffness matrix, δ is a global nodal displacement, and f is a global nodal force. This equation can be rewritten as:

$$\begin{pmatrix} K_{11} K_{12} \\ K_{12}^{T} K_{22} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix} = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} \tag{1}$$

where δ_1 is the displacement of the moving and static nodes, δ_2 is the displacement of the free and sliding nodes to be determined. The parameter f_1 is the nodal force on the moving and static nodes, and f_2 is the nodal force acting on both free and sliding nodes. The nodal force of the free nodes is assumed to be zero, and only tangential nodal forces along the contacting bone surface are considered for the sliding nodes [2].

The final value of δ_2 is calculated by iteratively updating δ_2 using Eq. (2) until the converging condition is satisfied [described later].

$$\delta_2^{(k+1)} = \delta_2^{(k)} + \delta_{2\,update}^{(k)}, \, (k = 1, 2, \ldots..., n) \tag{2}$$

$\delta_{2\,update}$ is calculated as follows. First, f_2 is calculated by substituting current δ_2 into Eq. (3) that is derived from Eq. (1). At the start of the iteration (k = 1), the initial δ_2 is randomly assigned and substituted for δ_2 to solve Eq. (3). f_2 is composed of nodal force of the sliding nodes ($f_{2\,sliding}$) and the free nodes (f_{2free}).

$$f_2 = K_{12}^{T}\delta_1 + K_{22}\delta_2 \tag{3}$$

Second, f_2^t is calculated by transforming the nodal force of the sliding nodes among f_2 to have only tangential nodal force component [2]. Now, f_2^t is composed of the nodal force of the free nodes ($f_{2\,free}$) and only a tangential component of the nodal force of the sliding nodes ($f_{2\,sliding}^t$).

In the final step of the iteration, $f_{2\,update}$ is acquired to determine the required nodal displacement ($\delta_{2\,update}$). Nodal force $f_{2\,update}$ is the difference between f_2^t and f_2. $\delta_{2\,update}$ is finally calculated as follows: $\delta_{2\,update} = -K_{22}^{-1}\left(f_{2\,update} + K_{12}^T\delta_1\right)$, which is derived from Eq. (1). Then, $\delta_2^{(k+1)}$ is calculated using Eq. (2). The iteration continues until the maximal absolute value of $f_{2\,update}$ converges below 0.01 N ($k = n$). The final values of δ (δ_1 and δ_2) represents the displacement of mesh nodes after the appling bone movements and the simple sliding effect. The algorithm was implemented in MATLAB. The final δ in this first-stage simulation is designated as δ_{first}.

2.2 The Second Stage of FEM Simulation with Advanced Sliding Effect

The predicted facial soft tissue changes in the first stage are further refined in the second stage by adding an advanced sliding effect. This is necessary because the first stage only accounts for the nodal force constraint, which may result in a mismatch between the simulated mesh inner surface and the bone surface (Fig. 2).

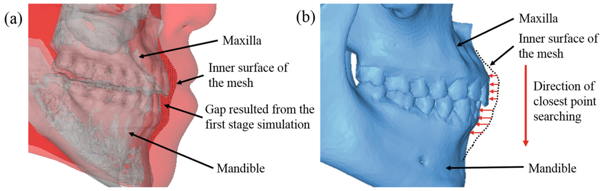

Fig. 2. Assignment of nodal displacement in the second stage of FEM. (a) Mismatch between the simulated mesh inner surface and the bone surface. (b) Description of nodal displacement boundary condition assignment.

Based on real clinical situations, the geometries of the teeth and bone buccal surface and its contacting surface on the inner side of the soft tissue mesh should exactly be matched, even though the relationship between the vertices of the bones and the nodes of the soft tissue mesh is changed after the bony segments are moved. Therefore, the boundary mapping and condition between the bone surface and soft tissue mesh nodes need to be reestablished in the sliding areas in order to properly reflect the above realistic sliding effect. First, the nodes of the inner mesh surface corresponding to the maxilla and mandible are assigned as the moving nodes in the second stage (*blue* in Fig. 1c). The nodal displacements of the moving nodes are calculated by finding the closest point from each mesh node to the bone surface, instead of finding them from the bone to the mesh in the first-stage. The assignment is processed from superior to inferior direction, ensuring an appropriate boundary condition implementation without mesh distortion (Fig. 2). This is because clinically the postoperative lower teeth are always inside of the upper teeth (as a normal bite) despite of the preoperative condition. This procedure prevents the nodes from having the same nodal displacement being counted twice, thus solving the mismatch problem between the bone surface and its contacting surface on the inner side of the simulated mesh. Once computed, the vector between each node and its corresponding closest vertex on the bone surface is assigned as the nodal displacement for the FEM simulation.

The free nodes at the inferoposterior surface of the soft tissue mesh in the first-stage are now assigned as static nodes in this stage (*orange* in Fig. 1b). The rest of the nodes are assigned as the free nodes (*GreenBlue* in Fig. 1b and c). The global stiffness matrix (K), the nodal displacement (δ) and the nodal force (f) are reorganized according to the new boundary conditions. The 2nd-stage results are calculated by solving Eq. (1). Based on the assumption that the nodal force of the free nodes, f_2, is zero (note no sliding nodes in the second-stage), the nodal displacement of the free nodes, δ_2, can be calculated as follows: $\delta_2 = -K_{22}^{-1} K_{12}^{T} \delta_1$ (from Eq. (1)). Then, the final δ (δ_1 and δ_2) is designated as δ_{second}. Finally, the overall nodal displacement is calculated by combining the resulted nodal displacements of the first (δ_{first}) and the second (δ_{second}) FEM simulations.

3 Quantitative and Qualitative Evaluations and Results

The evaluation was completed by using 30 randomly selected datasets of patients who had dentofacial deformity and underwent an orthognathic surgery [IRB0413-0045]. Each patient had a complete preoperative and postoperative CT scans.

The soft tissue prediction was completed using 3 methods: (1) the traditional FEM without considering the slide effect [1]; (2) the FEM with first-stage (simple) sliding effect by only considering the nodal force constraint; and (3) our novel FEM with two-stage sliding effects. All FEM meshes were generated by adapting our FEM template to the patient's individual 3D model [3]. In order to determine the actual movement vector of each bony segment, the postoperative patient's bone and soft tissue 3D CT models were registered to the preoperative ones at the cranium (surgically unmoved). The movement vector of each bony segment was calculated by moving the osteotomized segment from its preoperative original position to the postoperative position.

Finally, the simulated results were evaluated quantitatively and qualitatively. In the quantitative evaluation, displacement errors (absolute mean Euclidean distances) were calculated between the nodes on the simulated facial mesh and their corresponding points on the postoperative model. The evaluation was completed for the whole face and 8 sub-regions (Fig. 3). Repeated measures analysis of variance and its post-hoc tests were used to detect the statistically significant difference. In the qualitative evaluation, two maxillofacial surgeons who are experienced in orthognathic surgery together evaluated the results based on their clinical judgement and consensus. They were also blinded from the methods used for the simulation. The predicted results were compared to the postoperative ones using a binary visual analog scale (Unacceptable: the predicted result was not clinically realistic; Acceptable: the predicted result was clinically realistic and very similar to the postoperative outcome). Chi-square test was used to detect the statistical significant differences.

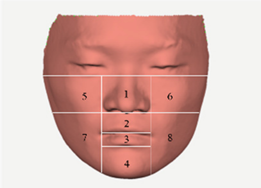

Fig. 3. Sub-regions (automatically divided using anatomical landmarks)

The results of the quantitative evaluation showed that our two-stage sliding effects FEM method significantly improved the accuracy of the whole face, as well as the critical areas (i.e., lips, nose and chin) in comparison with the traditional FEM method. The chin area also showed a trend of improvement (Table 1). Finally, the malar region showed a significant improvement due to the scar tissue modeling.

The results of the qualitative evaluation showed that 73 % (22/30) predicted results achieved with 2-stage FEM method were clinically acceptable. The prediction accuracy of the whole face and the critical regions (e.g., lips and nose) were significantly improved (Table 1). However, only 43 % (13/30) were acceptable with both traditional and simple sliding FEMs. This was mainly due to the poor lower lip prediction. Even though the cheek prediction was significantly improved in the simple sliding FEM, inaccurately predicted lower lips severely impacted the whole facial appearance.

Table 1. Improvement of the simple and 2-stage sliding over the traditional FEM method (%) for 30 patients.

Region	Quantitative evaluation		Qualitative evaluation	
	Simple sliding	Two-stage sliding	Simple sliding	Two-stage sliding
Entire face	1.9	4.5*	0.0	30.0*
1. Nose	7.2*	8.4*	0.0	0.0
2. Upper lip	−1.3	9.2*	13.3	20.0*
3. Lower lip	−12.0	10.2	−6.7	23.3*
4. Chin	−2.0	3.6	3.3	10.0
5. Right malar	6.1*	6.2*	0.0	0.0
6. Left malar	9.2*	8.8*	0.0	0.0
7. Right cheek	0.1	1.3	23.3*	23.3*
8. Left cheek	3.0	1.4	30.0*	30.0*

* Significant difference compared to the traditional method ($P < 0.05$).

Figure 4 illustrates the predicted results of a typical patient. Using the traditional FEM, the upper and lower lip moved together with the underlying bone segments without considering the sliding movement (1.4 mm of displacement error for the upper lip; 1.6 mm for the lower), resulting in large displacement errors (clinically unacceptable, Fig. 4(a)). The predicted upper lip using the simple sliding FEM was moderately improved (1.1 mm of error), while the lower lip showed a larger error (3.1 mm). The upper and lower lips were in a wrong relation (clinically unacceptable, Fig. 4(b)).

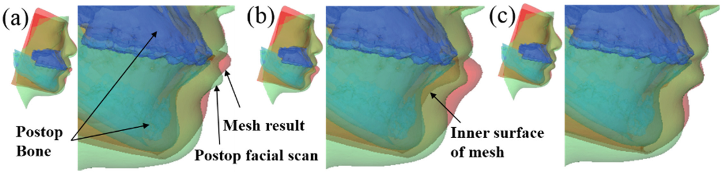

Fig. 4. An example of quantitative and qualitative evaluation results. The predicted mesh (red) is superimposed to the postoperative bone (blue) and soft tissue (grey). **(a)** Traditional FEM simulation (1.6 mm of error for the whole face, clinically not acceptable). **(b)** Simple sliding FEM simulation (1.6 mm of error, clinically not acceptable). **(c)** Two-stage FEM simulation (1.4 mm of error, clinically acceptable).

The mesh inner surface, and the bony/teeth geometries were also mismatched that should be perfectly matched clinically. Finally, our two-stage FEM simulation achieved the best results of accurately predicting clinically important facial features with a correct lip relation (the upper lip error: 0.9 mm; the lower: 1.3 mm, clinically acceptable, Fig. 4(c)).

4 Discussion and Future Work

We developed a novel two-stage FEM simulation method to accurately predict facial soft tissue changes following osteotomies. Our approach was quantitatively and qualitatively evaluated using 30 patient datasets. The clinical contribution of this method is significant. Our approach allows doctors to understand how the bony movements affect the facial soft tissues changes preoperatively, and subsequently revise the plan as needed. In addition, it also allows patients to foresee their postoperative facial appearance prior to the surgery (patient education). The technical contributions include: (1) Efficient 2-stage sliding effects are implemented into the FEM simulation model to predict realistic facial soft tissue changes following the osteotomies. (2) The extended definition of the boundary condition and the ability of changing node types during the simulation clearly solve the mesh distortion problem, not only in the sliding regions, but also in the bone collision areas where the proximal and distal segments meet. (3) The patient-specific soft tissue FEM model can be efficiently generated by deforming our FEM template, without the need of building FEM model for each patient. It makes the FEM simulation feasible for clinical use.

There are still some limitations in the current approach. Preoperative strained lower lip is not considered in the simulation. It can be automatically corrected to a reposed status in the surgery by a pure horizontal surgical movement. But the same is not true in the simulation. The 8 clinically unacceptable results using our two-stage FEM method were all due to this reason. We are working on solving this clinically observed phenomenon. In addition, we are also improving the error evaluation method. The quantitative results in this study do not necessary reflect the qualitative results as shown in Table 1 and Fig. 4. Nonetheless, our two-stage FEM simulation is the first step towards achieving a realistic facial soft-tissue-change prediction following osteotomies. In the near future, it will be fully tested in a larger clinical study.

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