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A 3D Virtual Orthognathic Surgery Planning and Simulation for the Prediction of Post-Operative Facial Appearance

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Abstract: This paper discusses the computerized surgery planning and simulation of an orthognathic surgery to virtually predict an after surgery (post-operative) facial appearance of a malformed faced patient. A three-dimensional patient specific facial model is reconstructed in combination of various geometrical modeling methods. These models composed of lower jaw, upper jaw and skin surface are optimized by manipulating a number of 3D model generation parameters such as method of interpolation, matrix reduction, smoothing and triangle reduction. This work employs the finite element analysis physics based model to incorporate appropriate tissue properties by providing exact mathematical modeling for the simulation of the jaw realignment to achieve balanced and functional aesthetics. Results of the simulated facial appearance are presented and validated.

Keywords: Virtual surgery, finite element analysis, soft tissue prediction, anatomy-based modeling, surgery planning.

I. INTRODUCTION

Over the past 100 years, since the discovery of X-ray, the development of medical imaging applications increased exponentially providing enhanced diagnosis, visualization, surgery planning and simulation for almost infinite medical areas [1,2,3]. The modern medical imaging technology such as computer tomography (CT) and magnetic resonance imaging (MRI) idealizes the generation of numerous 3D human anatomical models on computer systems. These models are capable of providing meaningful information thus offer the ability to perform difficult or technically impossible experiments on computer termed *in silico*. Thus, computer-assisted surgery (CAS) planning systems have been often used to model and simulate anatomical structures as realistic as it would in reality.

Orthognathic surgery is defined as a type of counteractive facial surgery giving focus on skull and respective facial components performed on patients with malformed facial to correct facial deformities and oral dysfunction. Through surgery planning on the computer, surgeons are able to conduct interactive simulations of the resulting tissue changes as to improve his planning process. The simulation outcomes are therefore available for analysis and further study. If one simulation does not yield expectation, the surgeon is able to undo the process or perform another virtual operation. Thus, this technique produces better surgical planning as it reduces costs and saves time.

Two common mathematical computation methods used to simulate the surgical procedures in order to predict the post surgical facial appearance are mass-spring systems [4,5] and finite element method(FEM) [6,7]. Both techniques have proven [8,9,10] acceptable for the simulation and prediction of soft tissue changes for orthognathic surgery. The mass–spring systems models skin and bone as points connected by springs while FEM commonly models the facial anatomy with finite simple elements such as triangular, tetrahedral or quadrilateral elements joined at node points. The FEM is a better option as material properties of a particular tissue can be incorporated during analysis to achieve realistic results.

The overview of the paper is as follows. Section II introduces the approaches employed for surgery planning where preparation of anatomy based modeling is described in Section II.1. Methods to achieve optimized facial models are detailed in Section II.2 followed by individualized surgery planning that involves bone cutting and repositioning in Section II.3. Section III delineates the finite element modeling. Section IV illuminates results and validation of post surgery outcome followed by conclusion and future works in Section V.

II. SURGERY PLANNING

1. 3D Facial Anatomy Modeling

The initial procedure that serves the foundation of computerized orthognathic surgery planning is the reconstruction of adequate three-dimensional facial models based on actual computer CT patient data. This task is called *triangulation* where consecutive pixel-based CT images are converted into triangular meshes particular to the desired geometries by employing the Marching Cube Algorithm [11]. In this work, the major facial anatomy employed are the facial skin layer, upper jaw and lower jaw for which each model is separately extracted through thresholding by selecting appropriate region of interest on the CT images. Along the procedure, contrast adjustments called *windowing* is performed on the image slices in order to enhance visibility of variable tissue densities. The first attempt of triangulation depicted in Fig. 1 produces excessive thresholded points, thus these pixels are manually removed although it can be a time consuming task. In addition, parts which appeared defective due to metallic objects of metal teeth filling are further preprocessed. However, pixels which have been unintentionally eliminated through the manual editing operation are recreated during the quality enhancements process.

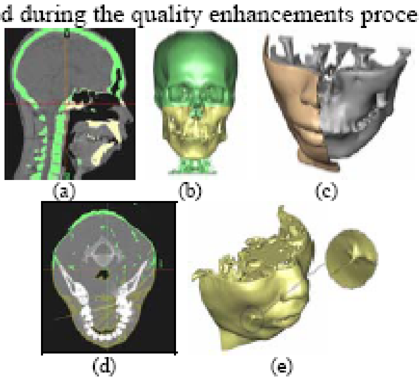

Fig. 1: Geometrical data sets. (a): Computer Tomography image slice, (b): Patient specific 3D facial model, (c): Facial model without soft tissue, (d): Bright spots on CT image caused by metal filling in the teeth, (e): Distorted 3D models due to artifact

2. 3D Generation Parameters

The generated facial models are saved as the STL format. The STL interface will generate a triangle mesh around the selected volume where each surface pixel of the segmented CT image results to two or six triangles. The numbers of triangles determine the quality of reconstruction which means more triangles gives higher quality model. However, the drawback is that more triangles certainly require more memory for the generation of a facial model. Therefore a number of parameters are manipulated for optimized facial models used for the finite element analysis.

A. Method of Interpolation

Two options available for image interpolation and 3D triangular mesh generation are *grey value* interpolation and *contour* interpolation. The *grey value* interpolation is constructed based on real 3D interpolation and thus more accurate as during the process of connecting points for the triangular mesh generation, preceding and succeeding CT images of the neighboring points are considered. This gives attention to the details in correct dimension and positioning. However, unnecessary details are produced due to the noise within the images. Hence, results to inadequate results as shown on Fig. 2(a). On the other hand, the *contour* interpolation is a 2D interpolation in the plane of CT images smoothly expanded in the third dimension. The *contour* interpolation method uses *grey value* interpolation within the images which produces smoother 3D results of reduced gaps as shown on Fig. 2(b). Hence, the *contour* interpolation is best employed.

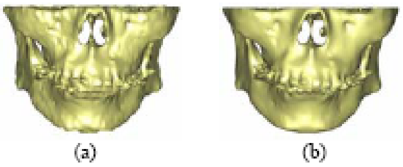

Fig. 2: Interpolation with continuity algorithm. (a): Grey value, (b): Contour.

B. Matrix Reduction

The matrix reduction algorithm is used to group voxels for triangulation. Reduction is made on the count of numbers of voxels in respectively X-plane, Y-plane and Z-plane. The X- and Y-planes refer to the size of pixel while the Z-direction for the height. Two types of matrix reduction algorithms are *continuity* and *accuracy*. *Accuracy* algorithm as the term explains gives accurate model dimension but less nice results because gaps appear when wall thickness of the geometry is smaller than the pixel size. On the contrary, *continuity* algorithm generates nice results with larger 3D dimensions when bigger matrix reduction is used. Therefore, the *continuity* algorithm is of choice in this work simply for the reason that medical applications demands good quality models to work on. Fig. 3 shows partial skull reconstruction similar to Fig. 2 using the *accuracy* algorithm correspondingly for *contour* and *grey value* interpolation. Fig. 3 reconstructs the skull model by employing *continuity* algorithm.

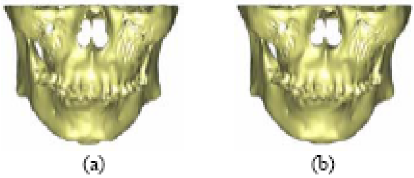

Fig. 3: Interpolation with accuracy algorithm. (a): Grey value, (b): Contour.

C. Smoothing

Smoothing is performed to filter noise to ensure rough surfaces smoother. However, the smoothing process does not contribute to triangle reduction to the considered facial models. The number of 3 iteration cycles is sufficient to produce smoother surface. Higher values will alter the actual shape of the facial models.

D. Triangle reduction

The triangle reduction algorithm reduces the number of triangles in a mesh. Two triangle reduction types are *point-type* and *edge-type*. The *point based* removes points to reduce the quantity of triangles whereas the *edge-type* removes a triangle edge of two vertexes and connecting line between two associated points. The *edge-type* is employed as less noise is introduced to the generated facial models. An edge angle is measured between the normals of a triangle. A benchmark value is selected for which triangles deviating less than the selected angle is eliminated. However, assigning high angle values as point of reference will cause improper deviations that lead to less determined edges hence more triangle reduction. This is not a good practice as geometry preservation is more important than reducing the numbers of triangles.

3. Osteotomy

On completion of appropriate model preparation, an important procedure for the surgery planning called *osteotomy* is performed. *Osteotomy* is defined as bone cuts to the craniofacial region which range from upper jaw to the lower jaw of an individual. In the example case, a mandibular *osteotomy* is executed in which part of the lower jaw bone is cut and advanced forward in proportion to the upper jaw. Fig. 4 shows the bone cuts and repositioning of the new bone slices.

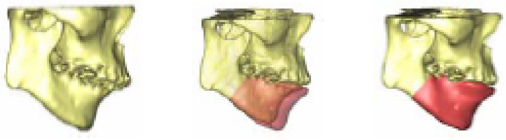
(a) (b) (c)

Fig. 4: Skull before and after *osteotomy*. (a): Original skull, (b): Semi-transparent surface and (c): Solid surface

III. FINITE ELEMENT SURGERY SIMULATION

In considering simplifying assumptions, the optimized facial models of lower jaw, upper jaw and the lower facial skin surface prepared during surgery planning are used for the virtual orthognathic surgery simulation through finite element analysis to predict the after surgery facial appearance of the individualized patient. Prediction of post surgical appearance is done by means of simulation of the repositioned lower jaw due to *osteotomy* movement explained in Section II.3 through simulation by finite element analysis.

The finite element method provides exact mathematical modeling for the representation of soft tissue behavior of the facial model. Due to the capacity of replicating models close to physical reality, the finite element analysis (FEA) allows solution approximation of complex models or problems without theoretical solutions. The concept of FEA defines that a model is divided into finite numbers of simple elements such as triangles or quadrilaterals in which every element is bonded at a point called nodes. Mathematical equations representing physical characteristics of bone and skin tissues such as elasticity, stiffness, density and thickness are used to calculate the behavior of every element. Hence, solution of the entire model is definite for the assembly of all calculations of each element.

The facial models prepared during surgery planning are rebuilt to compose quadrilateral elements. This procedure is termed *meshing*. Mechanical behavior of each element is computed through the shape function, N_i of *Galerkin* differential method for linear two dimensional isoparametric elements as shown in (1)

$$N_i = \frac{1}{4}(1+\xi_0)(1+\eta_0) \qquad (1)$$

where ξ_0 and η_0 are local coordinates of the elements.

Biological tissues are known to acquire behaviors of *anisotropic*, *non-homogeneous* and non-linear [12,13]. However, due to constitutive models constraints the facial models employed for this work are assumed *isotropic*, *homogeneous* and linear elastic.

Strain behavior for every quadrilateral element, ε(x) is calculated by

$$\varepsilon(x) = Ba \qquad (2)$$

where a defines a node for each element and B describes the strain displacement matrix.

Stress behavior for every quadrilateral element, σ(x) that determines the linear property of soft tissue is defined by Hooke's law through (3)

$$\sigma(x) = E\varepsilon(x) \qquad (3)$$

where E represents Young's modulus that is assigned during the analysis setup.

Homogeneous property which is also assigned during the analysis setup describes that tissues are composed of a single layer material. The skin material is assumed *isotropic*, a condition where elastic properties are identical in all directions are defined by the modulus of rigidity, G and *Lamé* constant, λ based on (4)

$$\lambda = \frac{\nu E}{(1+\nu)(1-2)} \qquad G = \frac{E}{2(1+\nu)} \qquad (4)$$

Equations (4) is used to derive the constitutive equation for an *isotropic* linear elastic material which is governed by (5)

$$\sigma_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + 2G\varepsilon_{ij} \qquad (5)$$

where σ_{ij} is shear stress in $_{ij}$ plane, δ_{ij} is Kroneker delta, ε_{kk} is normal strain parallel to k^{th} axis and ε_{ij} is shear strain in $_{ij}$ plane.

All elements are assembled to form global equation system for continuity of all elements and to equilibrate the structure with its environment (6)

$$Ka + f = 0 \qquad (6)$$

where K defines stiffness matrix, a is the nodal point and f describes the load at each nodal point.

Boundary conditions called *displacement* are incorporated with (6) during the solution. On completion of the analysis, facial models of the skull and skin surface is displaced to a new position and the facial skin changes are simulated and visualized.

IV. RESULTS & VALIDATION

Simulation of the soft tissue deformation of liner elastic finite element analysis is initially tested on artificial objects. Fig. 5 shows the predicted soft tissue represented by deformation changes of a cylinder and tissue block which employs material properties values used on the actual soft tissue prediction simulation.

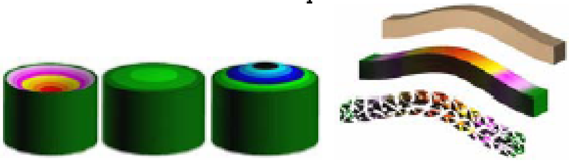
(a) (b)

Fig. 5: Simulation of soft tissue deformation shown on a (a): cylinder and (b): tissue block

The predicted postoperative appearance achieved under the impact of lower jaw repositioning through finite element analysis is depicted in Fig. 6. The various colors on the facial skin in Fig. 6 determine the stress distribution calculated throughout the simulation. Hot colors such as red, orange and yellow represent higher value stresses while cold colors such as blue, green and pink represent lower value stresses.

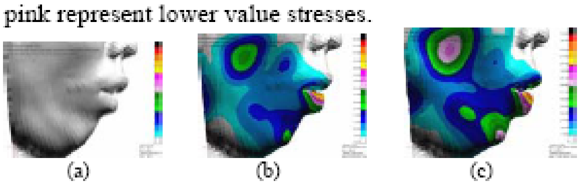
(a) (b) (c)

Fig. 6: Simulation of the facial appearance prediction shown on (a): actual outlook, (b): simulation process with FEA, (c): predicted post-operative appearance.

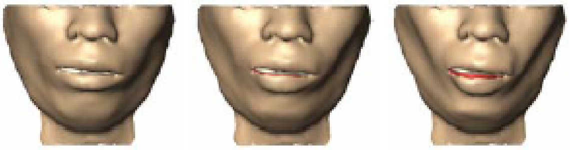

Fig. 7: The frontal views of the simulated and predicted facial appearance.

Fig. 7 shows visually realistic results of the initial and predicted appearance. The simulated result is qualitatively validated with actual photograph of the example patient as illustrated in Fig. 8. Although the qualitative result does not conform to accurate result which is believed due to the linear constitutive equations constraint, the predicted findings are sufficiently acceptable.

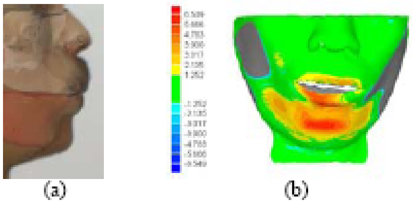
(a) (b)

Fig. 8: (a) Qualitative validation and (b) Quantitative evaluation.

Color map pseudo-coloring technique is employed for the representation of distances between the postoperative simulated results with the actual results. The quantitative evaluation of Fig. 8 illustrates large differences of facial changes with hot colors such as red, orange and yellow while minimal affected facial region is denoted by cold colors of blue having green as unaffected areas between the mappings of simulated and actual results. This finding supports the reason that major facial changes of the lower jaw relocation occurred within the chin region.

V. CONCLUSION & FUTURE WORK

We have presented a prototype system capable of performing mandibular advancement surgery planning and facial soft tissue simulation to produce harmonious and balanced appearance. Patient-specific facial models are generated based on Asian CT data of Malay ethnicity where physics based method of finite element analysis is incorporated to resemble real human facial anatomy and behavior through appropriate physical characteristics of tissues such as elasticity, stiffness, density and thickness. Although the current result is inaccurate, the presented approach has proven possible.

We are working towards improving current findings by experimenting non-linear elastic formulation. Accurate soft tissue prediction is possible by employing enhanced constitutive equations to suit the need of real tissue characteristics. Furthermore, advance anatomical features such as fat, muscular anatomy, and nerves would improve simulation results by introducing volumetric models composed of tetrahedral elements. Comprehensive understanding on muscular anatomy would allow simulation of dynamic facial expressions in addition to the predicted facial appearance. Current research has been tested on one example patient. More case studies ranging from diverse age, ethnicity and gender needed to be performed in order to achieve a reliable orthognathic surgery planning and simulation.

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