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3-D finite element modelling of facial soft tissue and preliminary application in orthodontics

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Prediction of soft tissue aesthetics is important for achieving an optimal outcome in orthodontic treatment planning. Previously, applicable procedures were mainly restricted to 2-D profile prediction. In this study, a generic 3-D finite element (FE) model of the craniofacial soft and hard tissue was constructed, and individualisation of the generic model based on cone beam CT data and mathematical transformation was investigated. The result indicated that patient-specific 3-D facial FE model including different layers of soft tissue could be obtained through mathematical model transformation. Average deviation between the transformed model and the real reconstructed one was 0.47 ± 0.77 mm and 0.75 ± 0.84 mm in soft and hard tissue, respectively. With boundary condition defined according to treatment plan, such FE model could be used to predict the result of orthodontic treatment on facial soft tissue.

Keywords: 3-D finite element modelling; facial soft tissue; model transformation; radial basis functions; orthodontic prediction

1. Introduction

A balanced soft tissue profile is a desired treatment objective in orthodontics. We can influence the lip profile by changing the position of incisors. So far in orthodontics, applicable procedures for profile prediction have been mainly restricted to 2-D methods (Riedel 1957; Bloom 1961; Rudee 1964; Garner 1974; Roos 1977; Waldman 1982; Lew 1989; Perkins and Staley 1993; Delis and Kalra 1995; Caplan 1997). However, the ratios established from cephalometric analysis vary a lot due to sample differences (e.g. age, race, sex, etc.). In addition, a full spatial prognosis of patient's post-treatment appearance is a more desired goal, which whereas cannot be accomplished with the 2-D method.

Recently, some 3-D finite element (FE) models of craniofacial structures were constructed with the purpose to assist preoperative planning of complex osteotomies in craniomaxillofacial surgery and postoperative facial soft tissue prediction (Delingette 1998; Keeve et al. 1998; Zachow et al. 2000, 2002; Chabanas et al. 2003; Holberg and Heine 2005; Holberg et al. 2005; Westermark et al. 2005). To our knowledge, a mature model integrating all the essential requirements for a sound clinical use does not yet exist. In addition, reports on modelling of facial soft tissue and its application in orthodontic treatment were seldom seen.

Change of the soft tissue that resulted from teeth movement alone will not be as much as that from bone reposition in maxillofacial surgery. Therefore, a more accurate individual biomechanical facial model integrating major muscles is needed for each orthodontic patient. In this study, a new way to three-dimensionally predict facial soft tissue changes after orthodontic treatment will be explored.

2. Material and methods

2.1 Construction of a generic model

Craniofacial spiral CT data (GE MEDICAL SYSTEMS/LightSpeed® *VCT*) of a volunteer with normal occlusion (volunteer A) was collected. The data were imported into *MIMICS® 11.0* software, which was well suited for the segmentation of anatomical structures out of tomographic data for image processing. After filtering to reduce noise and to delete redundant part, different tissue regions including facial skin, skeleton and anterior teeth (four first bicuspids included) were segmented and reconstructed via threshold values of the appropriate Hounsfield units.

In contrast to existing approaches (Holberg and Heine 2005; Holberg et al. 2005), we generated not only 3-D surface models of the craniofacial anatomy, but also a corresponding volumetric model (i.e. a FE model) for mechanical simulation. The planning model consisted of an inhomogeneous volumetric grid of tissue regions representing skin, muscle, fat and bone, as well as all polygonal boundary surfaces between different tissue types.

Facial skin has a layered structure composed of epidermis, dermis and hypodermis (mainly subcutaneous

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fat). Epidermis is the top layer about 0.1 mm thick. The dermis is much thicker (0.5–4.0 mm) containing blood vessels, nerves, hair roots and sweat glands. Subcutaneous fat lies on the muscles and skull, to which the whole skin structure is attached by connective tissues. The skin can move slightly over the skull. Due to the thin thickness of epidermis, in this study, dermis and epidermis were considered to be one layer together and the thickness was set to be 2.5 mm. The inner surface of dermis was considered as the outer surface of subcutaneous fat layer.

The skull surface is composed of many small areas and is full of gaps and holes. Such surface could not be used directly as the inner surface of subcutaneous fat in modelling. Considering that the function of skull surface in this study was to provide boundary conditions for muscles and subcutaneous fat, simplification of bone surface could therefore be applied. An envelope was built on the external of skull based on selected key points according to the skull configuration. This envelope was considered as the inner surface of subcutaneous fat layer.

Many facial muscles involved in mandible movements and production of facial expression are inserted between the skin layer and the underlying bone. Their organisation is complex with interweaving fibres of specific insertion points and orientations. In addition, their mechanical properties are quite different from skin layers. Therefore, facial soft tissues are highly anisotropic. A more accurate biomechanical facial model for orthodontic purpose must include facial muscles. In orthodontic treatment, teeth movement mainly affects the lower third of the face. Thus, in this study, seven pairs of main peri-oral muscles were selected for model construction. Position and outline of these muscles could be demonstrated through adjustment of the threshold value in the reconstruction image of spiral CT data. However, due to the thin thickness, irregular position and distribution, direct segmentation of these muscles was hard to achieve. Therefore, anatomic modelling of these muscles based on combined information from CT image, literatures and atlas was applied (Leeson and Leeson 1989; Clemente 1997; Williams 1999; Chabanas et al. 2003) (Figure 1).

Most of the muscles were bilaterally symmetrical. Totally, 14 muscles were built in the model. At the corner of the mouth, the orbicularis oris, risorius, zygomaticus major and depressor anguli oris were inserted together on the skin. A small circular tendon was set at the place as a juncture of these muscles (Figure 2). Since most part of the facial muscle was surrounded by subcutaneous fat layer, Boolean operation was applied to subtract the muscle part from the surrounding soft tissue layer. Then, the facial skin and muscles had public areas connecting each other at the boundary.

Finally, the model was meshed into tetrahedral elements. For interactive manipulation and fast numerical simulation, the model was of locally adaptive resolution, thus preserving detail in regions of interest (i.e. lower third soft tissue) and neglecting details in regions out of focus (such as cranial bone and brain). The final generic FE model consisted of approximately 1.08 million nodes and 730,000 tetrahedral elements (SOLID 92). On this volumetric grid, partial differential equations for elasto-mechanical analysis could be efficiently solved via FE methods.

This 3-D FE model including facial skin, muscle, skull and teeth was assumed to be a generic one which could be transformed into individual models based on chosen landmarks.

2.2 *Individualisation of the generic model*

The generic FE model was connected by nodes and vertices of the elements. For any element, there was a set of corresponding nodes. A one-to-one correspondence existed between the element and the set of nodes. When spatial position of a node was changed, the elements containing this node would have a geometric deformation while keeping its mechanical properties unchanged. If all nodes of the model moved to their new coordinates based on a certain mathematic method according to landmark points, the whole model would be transformed into another

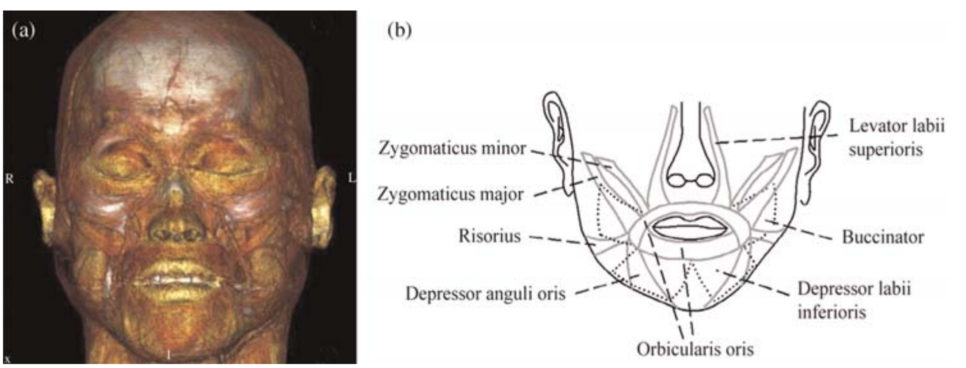

Figure 1. Main peri-oral muscles. (a) CT reconstruction image. (b) Schematic diagram of the seven pairs of peri-oral muscles selected for modelling.

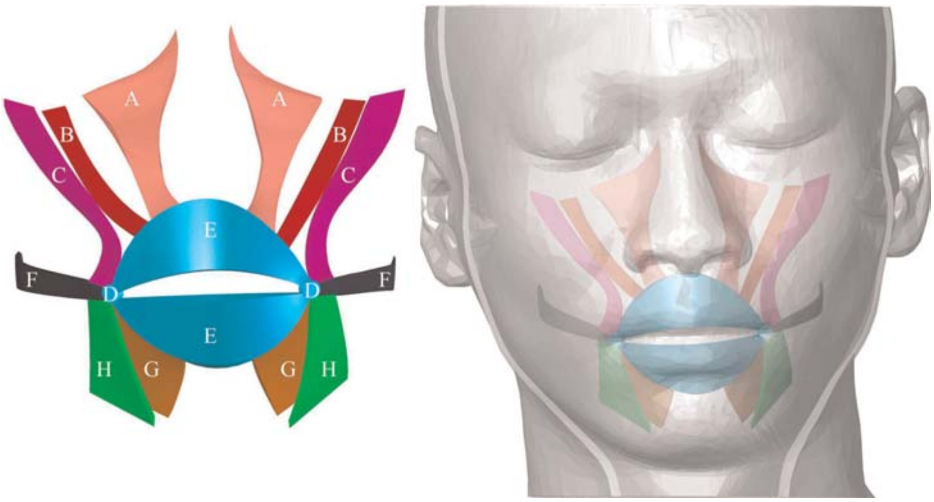

Figure 2. The muscles tendon, and a view of muscles in the skin: levator labii superioris (A), zygomaticus minor (B), zygomaticus major (C), tendon (D), orbicularis oris (E), risorius (F), depressor labii inferioris (G) and depressor anguli oris (H).

geometric shape. In this way, the generic model could be transformed into an individual one. To realise such transformation, two problems need to be solved: selecting characteristic landmark points and finding a proper mathematic method.

Landmark points are points on the skull or face from which cranio-metric measurements can be taken. There are three basic types of landmarks: anatomical landmarks, mathematical landmarks and pseudo-landmarks. Landmarks used in the present study are mainly anatomical landmarks or one of the equated points on the curve of two anatomical landmarks. For the soft tissue, part selection of landmarks was based on Farkas' method for anthropometry of face (Farkas 1994). Characteristic landmarks that were representative of facial contour as well as easy to identify and locate were chosen, including midline landmarks, e.g. nasion (n), subnasion (Sn), gnathion (gn) and bilateral landmarks, e.g. endocanthion (en), exocanthion (ex) and

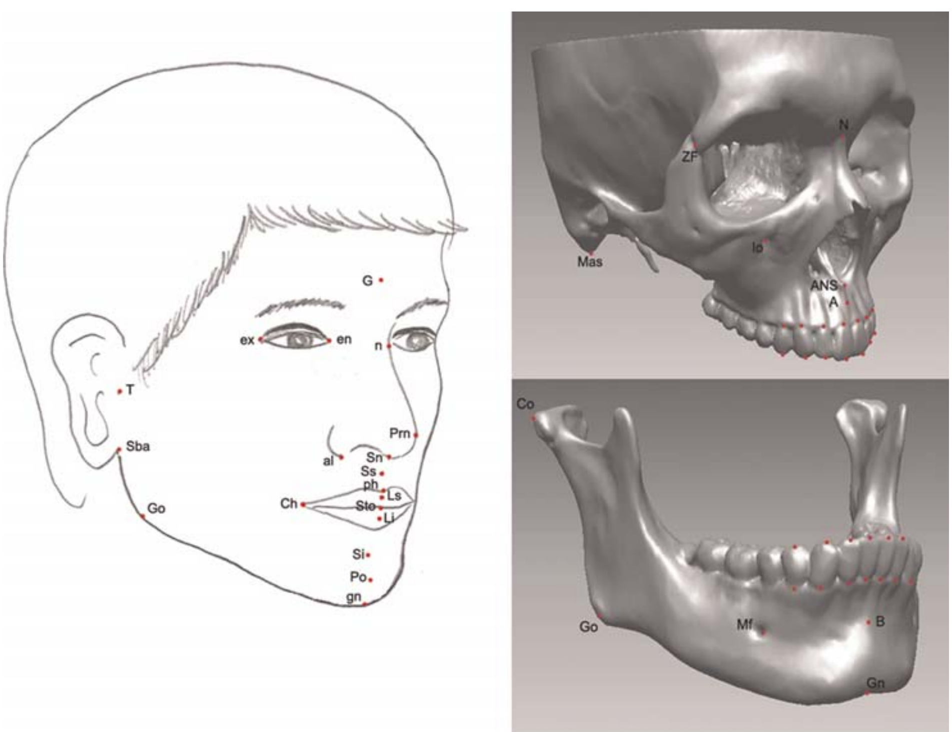

Figure 3. Soft and hard tissue anatomical landmarks used for transformation.

cheilion (ch). For the hard tissue, part landmarks that could represent skeletal and dental characteristics were selected, including skeletal landmarks, e.g. subspinale (A) and infraorbitale (Io) and dental landmarks, e.g. incisal and gingival midpoints of upper and lower anterior teeth. In all, 26 soft tissue and 49 hard tissue anatomical landmarks were selected for transformation (Figure 3).

In this study, the nodes on the envelope surfaces of the skull and on the connecting surfaces of the muscles to the skull were kept unmoved.

The nodes of the FE models were irregularly spaced. Therefore, a 3-D interpolation method was needed to calculate the new space positions of other nodes when landmark points moved. Frank (1982) compared different methods of scattered data interpolation and reported that the method of radial basis functions (RBF) had the best result. The method of RBF is one such method of scattered data interpolation over R^m that may use any number of landmark points $P_i (i = 1, 2, \ldots, n)$. A RBF interpolate through these points has the following form in three dimensions ($m = 3$) (Moroney and Turner 2007):

$$F(P) = \sum_{i=1}^{n} a_i \bullet \phi(\|P - P_i\|) + c + b_{11}x + b_{12}y + b_{13}z, \tag{1}$$

Where the function ϕ is a RBF, $a_i, c, b_{11}, b_{12}, b_{13}$ are coefficients and x, y, z are the coordinates of point p. Here, the multi-quadric $\phi(r) = \sqrt{r^2 + c^2}$ was chosen to be the RBF. The coefficients can be determined by solving the following square matrix system:

$$\begin{pmatrix} \phi(\|P_1 - P_1\|) & \cdots & \phi(\|P_1 - P_n\|) & 1 & x_1 & y_1 & z_1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \phi(\|P_n - P_1\|) & \cdots & \phi(\|P_n - P_n\|) & 1 & x_n & y_n & z_n \\ 1 & \cdots & 1 & 0 & \cdots & \cdots & 0 \\ x_1 & \cdots & x_n & \vdots & \ddots & \iddots & \vdots \\ y_1 & \cdots & y_n & \vdots & \iddots & \ddots & \vdots \\ z_1 & \cdots & z_n & 0 & \cdots & \cdots & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ \vdots \\ a_n \\ c \\ b_{11} \\ b_{12} \\ b_{13} \end{pmatrix} = \begin{pmatrix} F(P_1) \\ \vdots \\ F(P_n) \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \tag{2}$$

Applying the coefficients to Equation (1), the approximating solutions of other nodes would be gained.

In order to testify the effectiveness and accuracy of the above transformation method, cone beam CT (CBCT) data of another volunteer (volunteer B) were collected. CBCT as a relatively low-radiation technique permits all possible radiographs to be taken in less than 1 min. It might become a standard imaging strategy in future orthodontic treatment. If individualised FE model of clinical patient could be obtained through model transformation of the generic model using CBCT data, the procedure of modelling would be much simplified.

Corresponding soft and hard tissue landmarks were located on both volunteers' 3-D reconstruction models. Coordinates of these landmarks were imported to MATLAB®, in which interpolation would be done based on the method of RBF. Then, new coordinates of all nodes after transformation were obtained. Subsequently, the individualised 3-D FE model of volunteer B would be generated after importing the new set of node coordinates into ANSYS®.

3. Results

3.1 *Generic model constructed and individualised model transformed*

Figure 4 is the generic craniofacial FE model. Figure 5 shows the comparison between the transformed model and the reconstructed model of volunteer B. Superimpositions indicate the magnitude of deviation of the lower half facial area (red, +3 mm; yellow, +0.5 mm; green, ±0.4 mm; dark blue, −3 mm compared with CBCT reconstruction result). Average deviation between the transformed model and the real reconstructed one was 0.47 ± 0.77 mm and 0.75 ± 0.84 mm in the soft and hard tissue, respectively (Figure 5).

3.2 *Preliminary application in orthodontic treatment*

With the above-mentioned method, patient-specific FE model could be obtained through mathematical model transformation. With boundary condition defined according to the treatment plan, such FE model could be used to predict the result of orthodontic treatment on facial soft tissue.

In order to verify the feasibility and accuracy of such prediction, two patients' data were collected (Patient A was an adult and Patient B was a teenager). They all had four first premolars extracted and maximum anchorage designed using microscrew implant. From the superimposition of pre- and post-treatment CBCT data, the amount of anterior teeth retraction and anterior alveolar surface remodelling

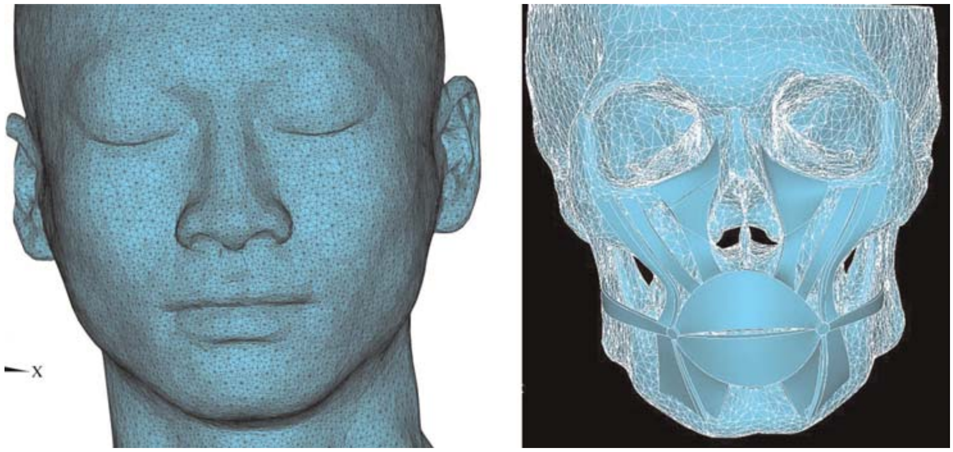

Figure 4. A generic craniofacial FE model including facial skin, muscle, skull and teeth.

could be gained and used as boundary condition. In this preliminary study, soft tissue of the model was assumed as isotropic and linear elastic material, having only two independent elastic constants, i.e. Poisson's ratio and Young's modulus. The value for Poisson's ratio ν was varied within the range of [0.3, 0.49] and Young's modulus E was varied within the range of 2,200 kPa (Manschot and Brakkee 1986; Duck 1991; Fung 1993; Zachow et al. 2004). Different values of ν and E were tested during simulation and the best correspondence between the simulation and the post-treatment result was found with elastic properties of soft tissues defined as follows: Poisson ratio ν for skin, muscle and fat was set as 0.45 while Young's modulus was set as 90, 6.2 and 2 kPa, respectively (Figure 6).

4. Discussion

In 2-D, many computer-assisted methods for profile prognosis exist, but they all rely on empirically determined ratios of questionable predictive accuracy. Using a volumetric, physics-based approach, we can predict a tissue deformation using elasto-mechanical properties of tissue. In the present study, firstly we constructed a generic craniofacial FE model including different soft tissue layers mainly based on spiral CT data. However, due to the characteristics of peri-oral muscles (e.g. thin and irregular) and limitation of present image data, direct segmentation of peri-oral muscles could not be achieved. Alternatively, anatomic modelling of seven pairs of main peri-oral muscles was applied based on the combined information from CT image, literatures and atlas. Difference between anatomic modelling and realistic distribution of peri-oral muscles may introduce errors to the constructed generic model. With the improvement of imaging system and post-processing software, these muscles might be segmented directly in future. This would improve the integrity and quality of the existing generic model.

Then, we explored the possibility of transforming the generic model into an individual one mathematically. The procedure of constructing a FE model integrating craniofacial anatomical structures was complicated and time consuming. It was unrealistic to repeat this complicated modelling procedure in clinical patients. If we could find a relatively simple way to transform the

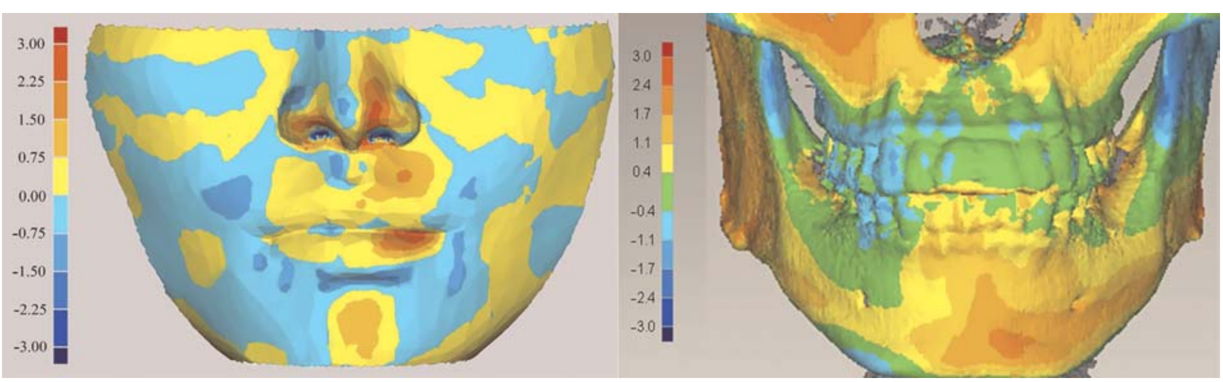

Figure 5. Average deviation between the transformed model and the real reconstructed one was 0.47 ± 0.77 mm and 0.75 ± 0.84 mm in the soft and hard tissue, respectively.

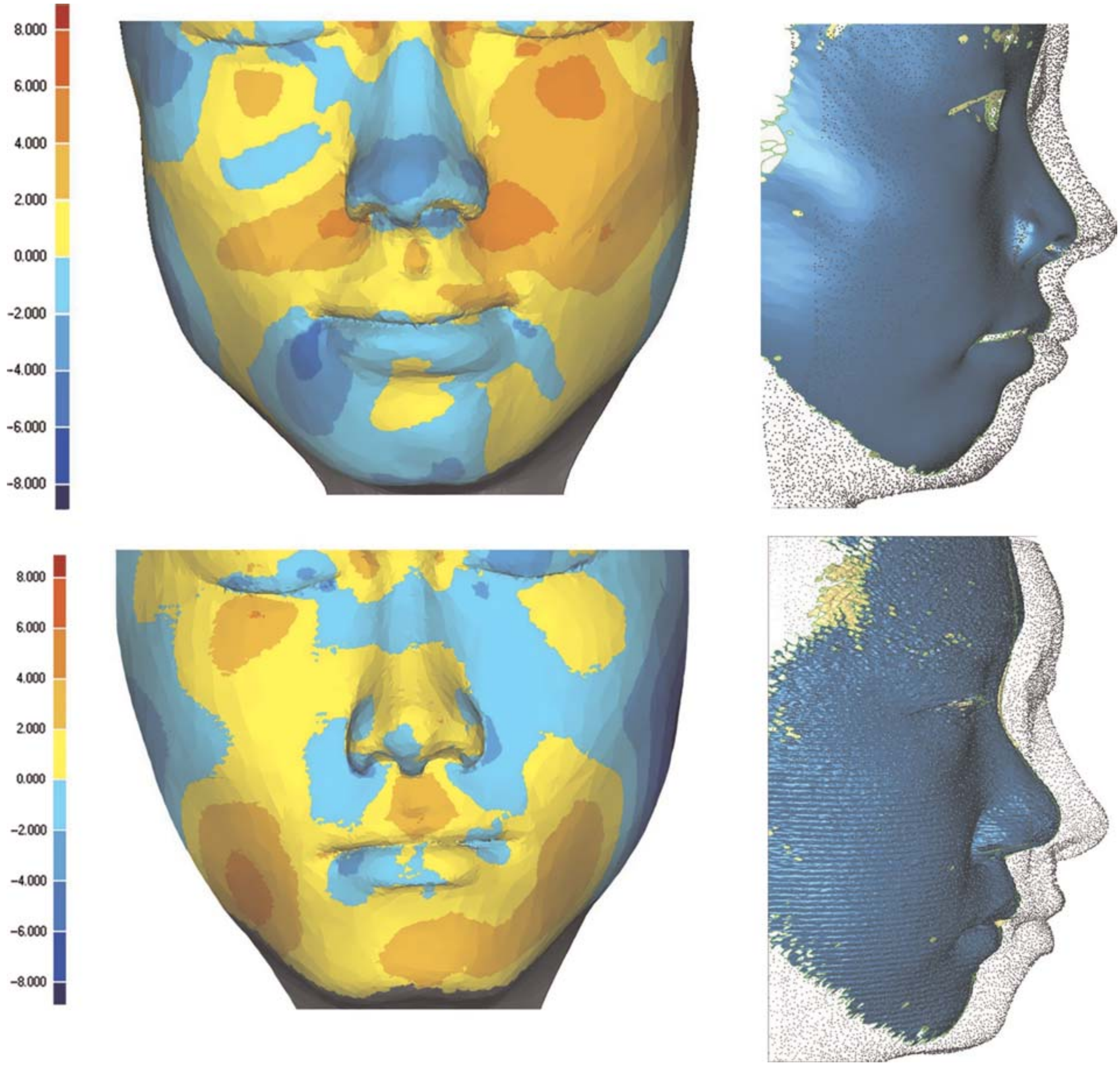

Figure 6. Comparison between the prediction and post-treatment results (top: Patient A, bottom: Patient B). Average deviation of the whole region and the lower third area was 2.28 ± 1.17 and 1.13 ± 0.86 mm, respectively, for Patient A. For Patient B, the average deviation was 2.56 ± 1.43 mm and 1.32 ± 0.93 mm, respectively. Profile comparison between the simulation and treatment result indicated that the prediction nicely coincided with the true outcome (blue: treatment result, grey: prediction result).

generic model into a patient specific one, the prospect for such FE model in future clinical application would be more promising. CBCT was a relatively low-radiation technique which could get plenty of volumetric information in a single shot. It might become a standard imaging strategy in future orthodontic treatment. To our knowledge, few studies have been carried out to use CBCT data and the transformation method to build patient-specific FE model in orthodontic filed. In this study, the method of constructing individual FE model based on CBCT data and mathematical transformation was tested. The landmarks used for transformation were mainly anatomical ones which were characteristic as well as easy to identify and locate. After importing coordinates of corresponding landmarks to certain program, new coordinates of all nodes were calculated out based on the method of RBF. Then, an individualised FE model was obtained. Such modelling procedure was much simplified, which increased the possibility of clinical application. At present, locating the landmarks was largely dependent on the subjective judgement of the operator. In future research, automatic registration based on surface information instead of landmark information will be investigated, which may decrease the influence of subjective judgment on the transformation result and increase the efficiency and accuracy of model individualisation.

Two clinical cases were selected to verify the feasibility of FE model simulation. In order to simplify the calculation procedure, in this preliminary study, the soft tissue was assumed as isotropic and linear elastic material. Due to the segmentation of skin, muscle and fat, piecewise homogenous approximation was applied. Therefore, different elastic properties were assigned to different soft tissue layers. Although initial application results indicated that the prediction result was close to the real treatment outcome, the deviations should not be neglected, which was partially due to the complicated biomechanical properties of facial soft tissue. In the future research, elastic properties of individual patient might be measured clinically. With the individualised parameters, nonlinear curve might be fitted and the accuracy of simulation would be improved.

In addition, a large part of orthodontic patients are teenagers who still have considerable growth potential. In the future study, predicted growth amount in treatment duration should be taken into account as part of the boundary condition to provide a better prediction result.

5. Conclusions

Patient-specific 3-D facial FE model including different layers of soft tissue could be obtained based on CBCT data and mathematical transformation. With boundary condition defined according to the treatment plan, such FE model could be used to predict the result of orthodontic treatment on facial soft tissue without using heuristic ratios. It could be also used in orthognathic surgery and prosthodontics. With such an approach possible, 3-D facial changes by different treatment strategies will be analysed and assessed more visually.

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