A volume-preserving free-form deformation technique for customizing face models between different configurations

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Abstract— **This article presents a volume-preserving free-form deformation technique that can be used to customize a face model generated from magnetic resonance (MR) images into another configuration using only the surface (skin) data. This customization process is useful when comparing anatomical measurements between datasets that may have undergone a different mode deformation. For example, gravity and other body forces were often neglected in most biomechanical simulations, and as a result, a supine face model generated from MR images is not suitable for analysis of activities performed in upright posture (i.e. expression detection for human computer interaction). To address this problem, the supine model can be fitted to the scanned skin data of an upright posture, in which conventional biomechanical simulations can be applied. Volume-preservation is an important characteristic of soft tissue deformation due to the high water content, and therefore is essential to produce realistic results, especially when only surface information is available. Validation studies presented in this article showed good agreement between the actual deformations and the predictions by the proposed method.**

Keywords— **Enter up to five keywords and separate them by commas.**

I. INTRODUCTION

An anatomically-detailed finite element model of the face will allow researchers to fully understand the mechanisms involved in the generation of facial expressions. A model of this capacity has many applications, such as for predicting the aesthetic and functional outcome from surgical interventions [1], to investigate speech articulation and phonological processes [2] and to generate realistic animations of facial expressions [3]. In all of these applications, the value of the model mainly depends on the geometric and anatomical accuracy of its internal structures (i.e. muscles). For this reason, these models are often created using the data derived from high resolution medical images.

However, medical imaging is often restrictive in terms of the scanning position, due to the confined space within the scanner. For example, conventional MR scanners require subjects to lie in either prone or supine position during the scanning session. This however, does not represent many of the practical settings, where the subject is usually in the upright position (e.g. sitting or standing postures), resulting in a different state of gravitational forces acting on the facial soft tissues. A convenient way to rectify this problem is to customize the face model to the desired configuration using only the surface topology that can be easily acquired from devices such as the structured-light surface scanner. Despite not being able to measure internal topology, structured-light systems are inexpensive and readily accessible, hence they are frequently used to determine facial geometries [4-6]. Furthermore, structured-light technique is fast and can be used to reproduce detailed surface data of an instance of an expression where it may be difficult to hold for a longer duration.

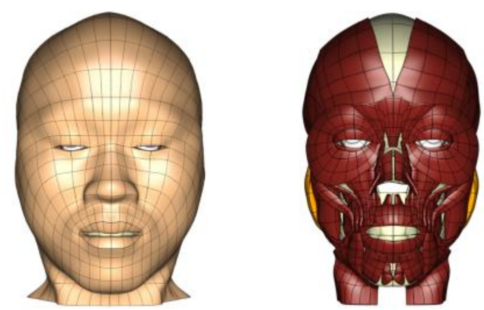

Fig. 1 Supine face model generated from MRI derived data showing the superficial fascia continuum (right) and embedded muscles (left).

This article presents a volume-preserving free form deformation technique that allows a supine face model (generated from MR data) to be customized into another deformed configuration, based exclusively on the skin data. Firstly, an iterative, volume-preserving surface fitting is performed to deform the face mesh, to conform its superficial surface to the scanned skin data. This is then followed by a host mesh customization procedure (a variant of free-form deformation), where information relevant to the transformation is passed onto the embedded internal structures. The anatomical data used for this study were collected from MR images of a healthy 26 year-old male volunteer. Fig. 1 illustrates the cubic Hermite finite element (FE) meshes [7] created from the anatomical data. The superficial fascia, that encompasses dermal layer, subcutaneous tissues and the superficial musculo-aponeurotic system [8], was considered as a single continuum due to strong kinematic coupling between these layers [9].

II. Method

A. Transformation of face mesh using surface data

In order to determine the transformation for customization procedure, the MRI-derived supine face model is first fitted to the scanned skin data using an iterative closest point (ICP) algorithm. A fitting objective function is set up which consists of a data term (F_D), a smoothing term (F_S) and a volume-preservation term (F_V). The data term is defined as the sum of the squared distance between the scanned data points ($\mathbf{x}_d$) and their closest points on the external surface of the FE mesh.

$$F_D = \sum_d \left\| \mathbf{x}(\boldsymbol{\xi}) - \mathbf{x}_d \right\|^2 \tag{1}$$

where, $\mathbf{x}(\boldsymbol{\xi})$ is the orthogonal projection of $\mathbf{x}_d$, interpolated at the element position $\boldsymbol{\xi}$=(ξ_1, ξ_2). The smoothing term is necessary to constrain the curvature of the surface elements at places where data points are sparse, scattered or noisy. The smoothing applied in this study is based on the Sobolev norms of the displacement field ($\Delta\mathbf{x}$).

$$F_S = \int \sum_i \alpha_i \left\| \frac{\partial \Delta\mathbf{x}(\boldsymbol{\xi})}{\partial \xi_i} \right\|^2 + \sum_{i,j} \beta_{ij} \left\| \frac{\partial^2 \Delta\mathbf{x}(\boldsymbol{\xi})}{\partial \xi_i \partial \xi_j} \right\|^2 da \tag{2}$$

where, α_i and β_{ij} are the smoothing weights for the first and second order Sobolev norms respectively. In addition, to ensure that internal material points deform in a physiologically realistic manner, the incompressibility constraint is appended to the fitting function to minimize volume change throughout the fitting process.

$$F_V = k \int (J - J_0)\, dv \tag{3}$$

In the volume-preservation term, k is the coefficient which penalizes for volume change, and J_0 and J are the determinants of the Jacobian matrix that describe the volume at the reference and final configurations respectively.

$$J = \left(\frac{\partial \mathbf{x}}{\partial \xi_1} \times \frac{\partial \mathbf{x}}{\partial \xi_2} \right) \cdot \frac{\partial \mathbf{x}}{\partial \xi_3} \tag{4}$$

B. Transformation of embedded muscle structures

Once the deformation of the face mesh is determined, the next step is to morph the muscular structures that are embedded inside the continuum (face mesh). This study uses an approach similar to the host mesh fitting technique described in [10]. Host mesh fitting is a variant of the free-form deformation (FFD) method where the host mesh is deformed, and passing on the transformation to the slave objects defined inside the host [11]. In this case, the host is the superficial fascia FE mesh, in which the transformation was obtained from the fitting process described in Section A, and the slaves are the muscles of facial expressions whose transformations need to be determined with respect to the deformed (transformed) host.

Since the slave muscles are completely embedded inside the host continuum, their nodal coordinates ($\mathbf{x}$) and derivatives ($\partial\mathbf{x}/\partial\eta_1$, $\partial\mathbf{x}/\partial\eta_2$,…, $\partial^3\mathbf{x}/\partial\eta_1\partial\eta_2\partial\eta_3$, with η_1, η_2, η_3 being the element coordinates of the slave mesh) can be readily defined by the host mesh parameters and their associated element coordinates (ξ_1, ξ_2, ξ_3). Moreover, the embedded material coordinates remain unchanged when the host deforms, and therefore, any deformation that the host experiences results in a corresponding deformation in the slave objects.

Given the Jacobian matrix [$\partial\mathbf{x}/\partial\boldsymbol{\xi}$] of the host at a slave node, the first derivative (with respective to η_1) at this particular node is defined as follows.

$$\frac{\partial \mathbf{x}}{\partial \eta_1} = \frac{\partial \mathbf{x}}{\partial \boldsymbol{\xi}} \times \frac{\partial \boldsymbol{\xi}}{\partial \eta_1} \tag{5}$$

Since the unknown vector [$\partial\boldsymbol{\xi}/\partial\eta_1$], which maps between the host and slave local coordinates, remains unchanged throughout the deformation. It can be determined at the reference configuration and substituted into equation 5 to obtain the first derivatives of the transformed slave node.

$$\left.\frac{\partial \mathbf{x}}{\partial \eta_1}\right|_t = \left.\frac{\partial \mathbf{x}}{\partial \boldsymbol{\xi}}\right|_t \times \frac{\partial \boldsymbol{\xi}}{\partial \eta_1} \tag{6}$$

where the subscript t represents tensors computed at the deformed configuration. The transformation of other derivatives at the slave node can be derived in a similar manner.

III. Validation Study

The validation of the customization method is crucial if it is to be used for wider applications. Since the structured-light scanning technique does not provide measurements of the internal structures, the described framework was validated by comparing MRI data in two other deformed configurations (Fig. 2) against predicted muscle deformation from the customization procedure. The first configuration considered was the prone-gravity-loaded configuration. This configuration allows us to assess the expected errors when customizing the MRI model to structured-light scanned data, which was also under a gravity loaded state but in the upright position (obtaining upright gravity loading configuration in the MRI machine was not possible due to space limitation). The second deformed configuration was produced by placing two plastic balls (20mm in diameter) inside the buccal cavity. This configuration mimics a puffing cheek and provides a very large strain in the mid-cheek

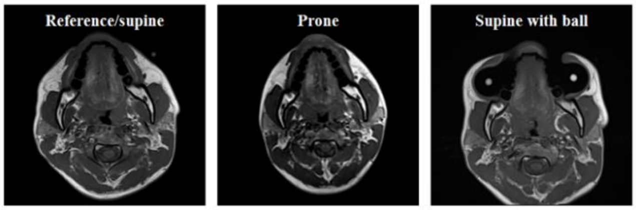

Fig. 2 MRI slices of the head in the reference (supine) position, prone position and supine position with balls placed inside the buccal cavity.

region which can be seen as an extreme case where surface data alone may not be sufficient.

For each deformed configuration, the following steps were performed.

1. The MRI data were first registered to the reference mesh position based on rigid features on the skin surface.
2. The registered MRI images were then segmented to extract skin-air boundary at places where deformation was prominent. In both examples, they were at the infra-orbital, zygomatic, buccal, oral and mental regions. These data points were then used for the surface fitting of the superficial fascia continuum mesh. Artificial data points were also generated at the muscle attachment sites to prevent unphysiological movement of the facial tissues.
3. As an error estimate, segmented muscle data were projected onto the external surfaces of the customized muscle meshes. Since the MRI data for both deformed configurations were acquired at a lower resolution, in order to minimize inconsistencies due to ambiguous boundaries, only muscles with clearly defined outlines were considered.

Table 1 RMS errors as a result of the finite element volume-preserving model customization.

Structure name	Initial RMS error (mm)	Customized RMS error (mm)	Absolute volume change (%)
a) prone-gravity-loaded configuration			
Superficial fascia	1.5	0.7	0.01
Zygomaticus major	1.6	0.9	
Orbicularis oris	1.1	0.8	
Depressor labii superioris	1.2	0.8	
Buccinator	1.0	0.8	
b) puffing cheek configuration			
Superficial fascia	4.8	0.8	0.14
Zygomaticus major	5.1	1.3	
Orbicularis oris	4.0	1.8	
Depressor labii superioris	2.7	1.5	

Table 1 summarizes the projection errors from the customization process. The initial RMS errors were obtained from the projections between segmented data and original meshes. This gave a reference point in which the performance of the customization procedure can be quantitatively assessed. The customized geometries are shown in Fig. 3.

Despite having a significantly smaller deformation for the prone-gravity-loaded configuration, the projection RMS errors were only half of that for the puffing cheek configuration. This is conceivably due to a base error associated with soft tissue artefacts. It is also worth noting that the projection errors displayed here are less than actual discrepancies. This is because the projection algorithm always finds the shortest distance between the data points and the mesh surface, and therefore does not track the actual movement of material points on the muscle mesh. However, regardless of these limitations, it is still observed that the customization procedure attempts to move the muscles in a general direction that reduces the projection errors.

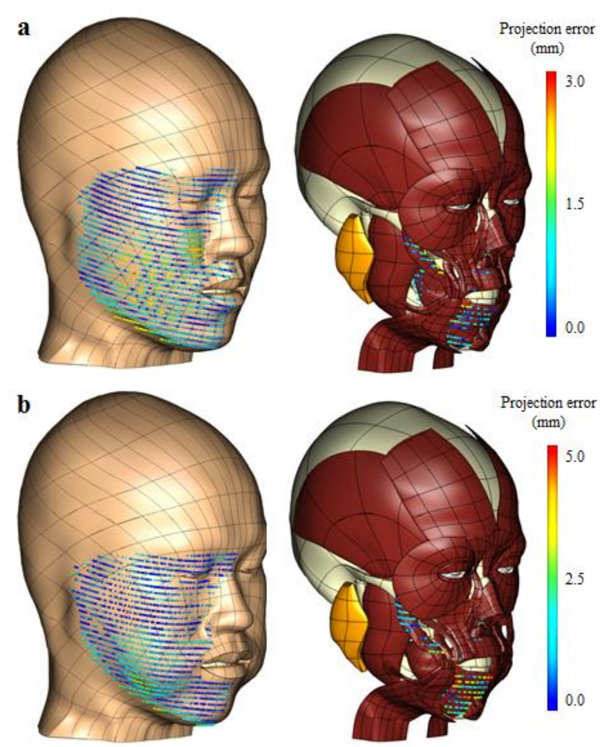

Fig. 3 Customization of supine head model to the (a) prone-gravity-loaded configuration and (b) puffing cheek configuration, showing the fitted surface errors and projection errors of selected customized muscles.

IV. Custumization Results

In most applications, it is required for model to be fitted to the upright configuration, such as in standing or sitting posture. In this study, the upright-gravity-loaded skin data were obtained from the Mephisto® EX-PRO structured light scanner (manufactured by 4DDynamics). Fig. 4 illustrates the projection errors associated with this customization process. This customized model is used for mechanics and statistical analysis to study facial expressive movements. Details regarding to these applications are given in [12, 13].

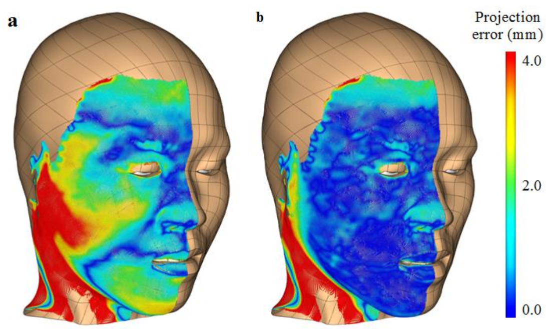

Fig. 4 Customization of face model from (a) the prone-gravity-loaded configuration to (b) the upright-gravity-loaded configuration, showing the projection errors from the structured-light surface data.

V. Conclusion

A technique based on the host mesh fitting method was used to customize the MRI-derived face model in the supine position to an upright posture using skin data obtained from a structured-light surface scanner. A volume preservation constraint was imposed during the fitting process to ensure the face continuum does not shrink or expand, hence satisfying the incompressible behavior of biological soft tissues. Moreover, with adjustment to the volume-preservation coefficient, the customization technique can also be used to rapidly morph the face model to another subject, which will effectively reduce the manual intensive effort when creating a population of face models.

Acknowledgment

The work presented in this article was funded by the Foundation for Research, Science and Technology of New Zealand (FRST) under the research grant contract number UOAX0712.

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