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Technical Section

Facial hexahedral mesh transferring by volumetric mapping based on harmonic fields

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ABSTRACT

Hexahedral mesh has obvious mechanical advantages over tetrahedral mesh, but it is no trivial task to generate hexahedral mesh for complex object shapes such as individual faces. This paper presents a novel method to generate patient-specific hexahedral meshes of facial soft tissue models, based on a volumetric cross-parameterization mapping from a standard hexahedral mesh to the individual model. The volumetric parameterization is constructed based on triple of the volumetric harmonic fields, which are adapted to be as close to mutually orthogonal as possible, to achieve some quasi-conformal effect. In addition, some piecewise constraints on the harmonic fields are added to ensure anatomical feature correspondence. Experimental results show that our approach works efficiently for facial soft tissue modeling, avoids element flipping and preserves mesh element angles to a significant extent.

1. Introduction

The use of the finite element method for biomechanical analysis has increased rapidly in recent years. For human bodies and organs, the main obstruction to such applications is the difficulty in constructing reliable finite element models. Owing to the complex shapes of biomechanical models, significant time and effort are required to construct reasonable finite element meshes.

There are two main classes of elements used for 3D solid finite element modeling, tetrahedral and hexahedral elements, each with their own advantages and disadvantages. Tetrahedral elements are geometrically versatile and can be reliably generated by many automatic meshing algorithms [1–3], even for models of complex shapes. On the other hand, a hexahedral mesh of good quality can vastly reduce the number of elements and, consequently, reduce the analysis and post-processing times. Compared with tetrahedra, hexahedra have better convergence and sensitivity to mesh orientation. In addition, hexahedral elements are more suited for non-linear analysis and for situations when the alignment of elements is important to the physics of the problem, such as in computational fluid dynamics or simulation of anisotropic materials.

So far, a number of hexahedral meshing approaches have been proposed: feature-based [4], medial surface subdivision [5] [6], plastering [7], grid-based [8], whisker weaving [9], etc. These traditional methods are mainly designed for regular CAD models and are not well suited for biomechanical models with irregular and complex shapes.

Furthermore, it is hard for direct meshing methods to generate appropriate mesh structures for biomechanical models with important anatomical features, e.g., the eyes, nose and mouth on the facial model. The underlying constraints that make hexahedral meshing difficult are presented by Shepherd and Johnson [10]. A promising solution to address the problem is to build some generic or standard mesh model of high quality one time, with all the manual effort necessary, and then conform and adapt it to patient-specific biomechanical models. The mesh-matching method [11], which is based on the elastic registration technique, is used to adapt the generic facial hexahedral mesh model to a patient-specific morphology [12]. However, this approach can produce flipped and self-intersected elements, requiring post-treatment algorithms and even manual modifications to detect and correct mesh element irregularity.

Another kind of mapping-based meshing method is to use a parameterization technique [13–17]. Gu et al. presented a robust method to compute harmonic volumetric maps based on a mesh-less boundary method [18], which depends on the initial boundary surface mapping and produces a good tetrahedral mesh. He et al. [19] proposed Green's function to parameterize star shaped volume domains inspired by the electric field of point charges to generate hexahedral mesh. However, He et al.'s method is not suitable for soft facial tissues, which do not resemble a star shape. Kraevoy and Sheffer [20] introduced a shape preserving cross-parameterization method for the compatible remeshing of 3D models. Recently, Martin et al. [21] proposed a volumetric parameterization method to fit a single trivariate B-spline. Lévy and Liu [22] introduced Lp-Centroidal Voronoi Tessellation for hexahedral dominant

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volume meshing. These automatic meshing methods do not utilize the standard hexahedral mesh to generate appropriate mesh structures for facial anatomical features.

Given an individual facial soft tissue represented initially by a tetrahedral mesh, the goal of this paper is to investigate a convenient method to produce a specific facial hexahedral mesh. The method generates a hexahedral mesh by mapping from a standardized facial hexahedral mesh of high quality and focuses on preserving the mesh element shape as well as important anatomical features.

In Section 2, we briefly discuss our design considerations. The details of our work are explained in Section 3. In Section 4, experimental results are reported and discussed. Finally, we present our conclusion in Section 5.

2. Design considerations

As mentioned above, it is difficult to generate hexahedral mesh structures directly for biomechanical models with irregular and complex shapes. In dealing with facial soft tissue models, it is especially hard to generate appropriate mesh structures for important anatomical features, such as the eyes, nose and mouth. Thus, the best solution is to generate the individual hexahedral mesh by working from a standardized hexahedral mesh that is based on volumetric mapping. Obviously, the volumetric mapping employed should retain the element shape qualities as much as possible; so conformal parameterization, which preserves angles, is a natural choice. For the mesh deformation domain, Huang et al. [23,24] introduced a shell generation and deformation algorithm that minimizes the difference between the deformation gradient and its orthogonal part. Given a closed two-manifold and the user-specified thickness, Han et al. proposed a method to construct a layered hexahedral mesh for shell objects via a volumetric polycube map [25]. For the surface domain, Gu and Yau [16] proposed an approach to construct conformal parameterizations for surface meshes, which takes advantage of the fact that the gradient fields of the conformal parameterization are holomorphic one-forms. The holomorphic one-forms can be represented as pairs of harmonic and orthogonal gradient vector fields and calculated automatically from the surface topology structure. However, there is no theoretical agreement about what the conformal volumetric parameterization should be for general volumetric domain.

In this paper, we present a method to construct the volumetric parameterization for special volumetric domains such as soft facial tissue regions, which construct triple of the orthogonal (or as nearly so as possible) harmonic volumetric fields, to achieve some quasi-conformal mapping effect. With the volumetric cross-parameterization mapping, we can adapt a standard hexahedral mesh to the patient-specific morphology. Fig. 1 shows a building block diagram that describes our overall system.

First, we construct a standard hexahedral mesh of high quality, which has appropriate mesh structures for all the important anatomical features, such as the eyes, nose and mouth, and can be reused later for all the patient-specific facial models.

Then, we construct volumetric parameterizations for both the standard model and the personalized facial model. The key issue here is how to construct the set of three harmonic volumetric fields, which can be used as the gradient fields of the volumetric parameterization,. that is, these harmonic fields need to be as close as possible to be mutually orthogonal. Furthermore, it is important to ensure correspondence to anatomical features, such as the eyes, nose and mouth.

Finally, using the same volumetric parameterization domain, we combine these two volumetric parameterizations, with one of them reversed, to create the volumetric mapping from the standard model to personalized facial model, which is then employed to generate the desired patient-specific hexahedral mesh.

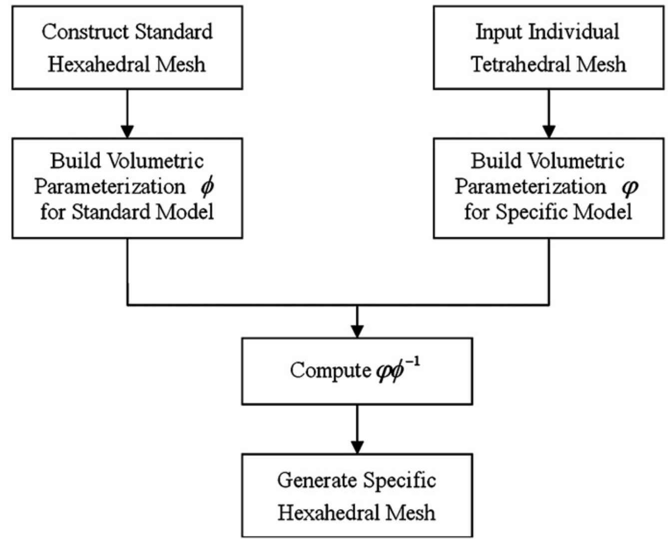

Fig. 1. Building blocks diagram for our overall system.

3. System description

3.1. Constructing a standard hexahedral mesh

The human facial soft tissue is a complicated shape, with important anatomical features, such as the eyes, nose and mouth. The automatic generation of appropriate hexahedral mesh structures for these regions is very difficult. Therefore, we designed some interactive and semi-automatic tools to create, together with manual modification methods, a standard hexahedral mesh of high quality. Note that the standard hexahedral mesh is constructed only once and will be used repeatedly for all patient-specific facial models. We believe that the need for manual interaction here will not restrict the applicability of our method.

As one usually focuses on the frontal region of the facial model when simulating physical behavior, we ignore the soft tissue above the forehead and behind the ears, as shown in Fig. 2. Loosely speaking, this makes the facial soft tissue region appear roughly like a bended thin cuboid, with three obvious axes: from left to right, from bottom to top and from inside to outside. These axes can be used as appropriate boundary conditions later to generate three quasi-conjugate harmonic fields.

Our semi-automatic modeling tool also takes advantage of this configuration, which can be further improved by quadrilateral meshing methods [26,27]. An initial quadrilateral mesh for the outer surface of the standard facial triangular model input is generated by cutting operations. Vertical and horizontal curves are produced by plane sections and connected to generate the initial quadrilateral mesh. Because there is no need for dense hexahedral meshes, a sparse quadrilateral mesh composed of 700 quadrilaterals is created. Then regions of significant anatomical features, such as the eyes, nose and mouth, are carefully modified to achieve a more appropriate mesh structure and preserve the anatomical features. Note that a few triangular elements are manually inserted to improve the adjacent quadrilateral quality and obtain a more appropriate mesh structure, but this will not lead to problems in post-processing and is common in finite element analysis.