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Effect of orthotropic material on finite element modeling of completely dentate mandible

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ABSTRACT

The objective of this investigation is to construct a high quality complete dentate mandible model with detailed biological structures, and assign mandibular bone with inherent orthotropic material characteristics. Three different types of scan data are used to elaborate detailed mandibular structures, including the cortical and cancellous bone, tooth enamel, dentin, periodontal ligament, temporal fossa, TMJ articular disk, temporal cartilage, and condylar cartilage. In addition, an extended orthotropic material assignment methodology based on harmonic fields is used to handle the alveolar ridge region of dentate mandible, to generate compatible orthotropic axes fields. The influence of orthotropic material on the biomechanical behavior of complete dentate mandible is analyzed compared with commonly used isotropic model. The result revealed that the orthotropic model would induce higher stress values and more well-distributed stress pattern than the isotropic model, especially for the cancellous bone. And the orthotropic model would induce lower volumetric strain values than the isotropic model on the cortical bone. It was concluded that elastic orthotropy had a significant effect on the simulated stress value and distribution pattern, as well as the volumetric strain, and demonstrated the mechanical optimality of the mandible.

1. Introduction

The application of finite element analysis (FEA) to skeletal mechanics has changed since this method was first introduced. A large number of efforts are made to mimic the material bone and the process by which it forms [1]. During mastication and biting, the mandible is subjected to forces produced by the muscles of mastication and by reaction forces applied to the temporomandibular joints and the teeth [2]. An understanding of the biomechanics of the mandible is important for several reasons, and it may give us an insight into the factors that determine mandibular bone structure, e.g., local anisotropic behavior and regional variations in bone tissues can have pronounced effects on the relationship between stress and strain patterns, which are directly related to bone adaptation and growth. But the stress and strain fields inside of bony organs in vivo can hardly be determined through direct experiments. As a numerical method for structure analysis that is suitable for complex biological structures, the use of finite element analysis in dental biomechanics has been increased in recent decades.

Conversely, the validity of the FEM results is primarily dependent upon three types of modeling factors [3]. The first factor is the similarity of the FE model to the real structure of the object to be analyzed. Excessive simplifications in geometry will inevitably result in considerable inaccuracy in the analysis. The second factor is associated with the modeling of the material properties of the structure studied. The improper setting of material parameters will lead to erroneous results. The third factor is the effectiveness of modeling the boundary conditions, i.e., the force loading and displacement boundary conditions.

Among the above three factors that determine the validity of FEM results, the boundary conditions can be modified interactively. By applying a new set of boundary conditions and re-executing the FEM software, one can readily obtain a new set of simulation results. In addition, the precise modeling of muscular actions during mastication is necessary to avoid significant errors in the stress and strain distribution [4].

Geometric modeling, however, is not a trivial task when one requires biological structures of high geometrical similarity. In recent years, most dental studies constructed the initial 3D models of the mandibular bone structures based on computerized tomography (CT) scan technology, which provides an efficient way to capture in vivo the complex geometry of human anatomy in the clinic. While the tooth root has similar bone density with the mandible in which it is embedded, the entire single tooth model is difficult to extract from CT data [5], and the reconstructed tooth crown usually lacks local feature details. Moreover, the biological soft tissues, such as the temporomandibular joint (TMJ) disk, articular cartilage, and periodontal ligament, are difficult to

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distinguish in CT scan. As a result, most previous studies have utilized simplified mandibular models without refined biological structures.

The assignment of proper material properties to the FE model is also a fundamental step to ensure predictive accuracy. The accurate modeling of biological tissues, such as bone related organs, is a very difficult task because of their inherent inhomogeneous and anisotropic characteristics [6]. The inhomogeneous property is, in a certain sense, "directly" accessible via the CT data based on the relationship between CT numbers, Hounsfield Units (HUs), and bone material properties [7,8]. Unfortunately, this accessibility is not the case for the trajectories of anisotropy. Without an automatic and well-defined assignment scheme, it is difficult to generate the orthotropic principal axes vector fields (orientation of the principal symmetry axes of orthotropy), which change from point to point inside the bone tissues. Most work performed in the physical modeling field has adopted oversimplified isotropic material law due to its simplicity.

Recently, Liao et al. investigated a convenient methodology for the physical FE modeling of bone tissues, integrated with complete and continuous orthotropic material [9]. The approach creates longitudinal and radial volumetric harmonic fields to generate the orthotropic principal axes vector fields, but only suitable for the edentulous mandible, as the scalar distribution cannot generate compatible direction field in the alveolar ridge region of the dentate mandible. Their new work proposed an extended orthotropic material assignment methodology to handle the alveolar ridge region of the dentate mandible, while, they only investigated the influence of orthotropy on biomechanics of peri-implant bone [10].

The objective of this study was to investigate the influence of orthotropic material on the biomechanical behavior of the completely dentate mandible, based on a high-quality, complete dentate mandible model with detailed biological structures, taking advantage of different types of data sources. Furthermore, the extended orthotropic material assignment methodology using harmonic fields was employed to handle the alveolar ridge region of the dentate mandible to generate compatible orthotropic axes fields.

2. Materials and methods

2.1. Model designs

The preparation work of FEA modeling represents the geometry of interest in the computer. In this study, three different types of data were collected to illustrate detailed mandible structures.

First, both CT and MRI scan datasets of a dentate mandible and temporomandibular joint (TMJ) of a 28-year-old man were used to produce 410 CT image slices and 65 MRI image slices in DICOM format. Scanned images were imported into the ad-hoc medical image processing and simulation software USIS (Universal Surgical Integration System), which stacks the images for visualization and segmentation based upon gray-scale density corresponding to different degrees of mineralization.

The initial 3D solid mandible (including the separation between cortical and cancellous bone) and parts of the temporal bone models were generated from CT scan data, and the solid models of the glenoid fossa, condyle and articular disk were built from the MRI scan data. Then, a 3D registration procedure based on the fossa and condyle regions was performed to transform the articular disk model of MRI data into the coordinate system of CT data.

Then, a laser scan digitizer (Cyberware) was employed to collect detailed geometric solid models of a group of standard plaster cast teeth. Based on a hybrid method using a level-set base shape prior to segmentation and thin plate spline transformation [5], each standard tooth model was used to create a best-fit geometric model of the patient-specific tooth on CT scan data, capturing the smooth tooth root as well as local details of the tooth crown.

Afterward, these individual tooth models were assembled and a Boolean operation was performed to generate the alveolar ridge in mandible bone. According to anatomical data from the literature, the separation surface between tooth enamel and dentin was built. The same procedure was used to generate the 1.2 mm-thick layer of TMJ articular cartilage on the fossa and condyle regions, and an average thickness of 0.25 mm was considered for the periodontal ligament around each tooth root.

The final assembled solid model is presented in Fig. 1, including the cortical and cancellous bone of the mandible, tooth enamel, dentin, periodontal ligament, temporal fossa, TMJ articular disk, temporal cartilage, and condylar cartilage.

These solid models were imported into the specially designed biomedical modeling program to generate the finite element volumetric mesh model [9], with adaptive mesh size that is optimal in the significant biomechanical region, e.g., around the tooth root and contact region of the temporomandibular joint.

2.2. Material properties

Two models with different material properties were built to study the influence of elastic orthotropy on the dentate mandible. In both cases, tooth enamel, dentin, and articular cartilage were considered to be isotropic, homogenous, and linearly elastic [11–14]: E = 84.1 GPa and $\nu = 0.33$ for tooth enamel, E = 18.6 GPa and $\nu = 0.31$ for dentin,

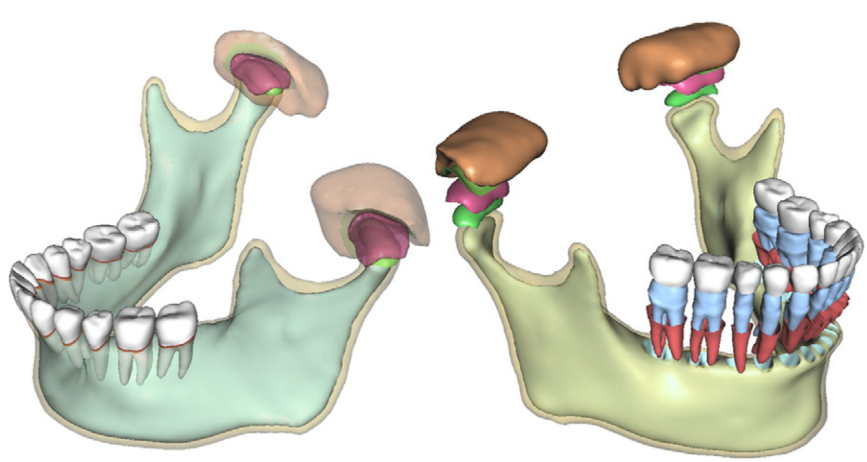

Fig. 1. The 3D assembled solid model of the completely dentate mandible.