HETEROGENEITY AND ANISOTROPY EFFECTS ON FINITE ELEMENT MODEL PREDICTIONS FOR A *MACACA FASCICULARIS* MANDIBLE

Ruxandra Marinescu, M.S.
Department of Biomedical Engineering
University of Florida
Gainesville, Florida
ruxi@ufl.edu

David J. Daegling, Ph.D.
Department of Anthropology
University of Florida
Gainesville, Florida
daegling@anthro.ufl.edu

Andrew J. Rapoff, Ph.D.
Department of Mechanical & Aerospace Engineering
University of Florida
Gainesville, Florida
rapoff@ufl.edu

ABSTRACT

The purpose of our work is to develop heterogeneous anisotropic finite element (FE) models of primate mandibles. These models will help to determine form and function relationships, with applications in a diverse set of disciplines (e.g., anthropology to orthodontics). Experimental research established that bones respond to the mechanical loads imposed on them, but the direct connection between bone form and mechanical stress history is not yet completely understood. The primate mandible is an ideal skeletal element for investigating the relationship of bone function to bone morphology because extensive documentation of the mechanics of mastication is available from numerous studies. The bone structure is analyzed through a new and ambitious approach that considers the spatial variations in material properties throughout the mandible. For this study, a *Macaca fascicularis* mandible was used because its stress environment *in vivo* is well understood.

INTRODUCTION

An established technique for analyzing and modeling stress distribution in bones is the FE method. The FE method requires accurate information on geometry, materials properties, loads and boundary conditions as input data. There are many studies that try to establish a connection between mandibular morphology and biomechanical stresses using this method. Usually, they treat bone as an isotropic material of uniform density, stiffness, and strength, and consequently, the stress analyses might generate substantial errors. Our work aims to improve upon mandibular modeling by including data on the heterogeneity and anisotropy of elastic properties, obtained from micromechanical tests.

METHODS

Experimental work included *in vitro* macromechanical and micromechanical tests on an adult female *Macaca fascicularis* mandible. All procedures were approved by our Institutional Animal Care and Use Committee. After computed tomography (CT) scanning (described next), the mandible was instrumented with rosette strain gauges on the lingual and labial cortices of the midramus (**Figure 1**). These tests permit the validation of the FE model. The specimen was subjected to incisal and occlusal loading in materials testing machine with constraints applied bilaterally at the condyles and angles. Elastic properties for the bone and dental tissues were obtained via microindentation testing. Briefly, the mandible was sectioned to expose multiple planes for microindentation. Sets of elastic moduli were converted to orthotropic engineering constants via elasticity transformation equations.

Figure 1. Macromechanical test on mandible.

The finite element model of the mandible is obtained in three stages: (1) 3D reconstruction of the model from multi-slice scanner data and segmentation, (2) building the NURBS model, and (3) meshing the imported NURBS model.

(1) Volumetric reconstruction was performed using 70 sagittal CT scans (**Figure 2**). The effective scan thickness was 1 mm (1.5 mm thick with 0.5 mm overlap). Resolution within each scan was less than 200 μm. Pixel grayscale depth was 24 bit. CT scans were individually segmented and a three-dimensional geometrical model was constructed. The 3D model was built automatically in

Tomovision Sliceomatic, a medical analysis software package, by overlapping all 2D images and populating the model with polygon surfaces. The mandible model was then exported as STL file.

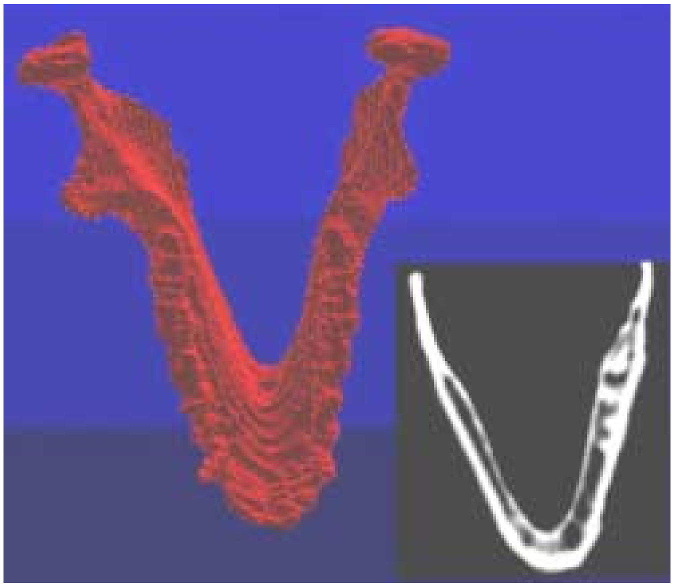

Figure 2. Volumetric reconstruction from CT scans.

(2) The NURBS model was constructed using Geomagic Studio, a 3D modeling software package (**Figure 3**). Since scan data is usually disorganized, using modeling software with edge reconstruction and hole filling capabilities is a much better choice, especially when the model is to be analyzed subsequently in a CAD/CAM application. After filling the gaps with polygons and editing the model, the polygon surfaces of the model are automatically converted into NURBS patches, using the NURBS surface modeling technique. The model was exported for finite element analysis as an IGES file.

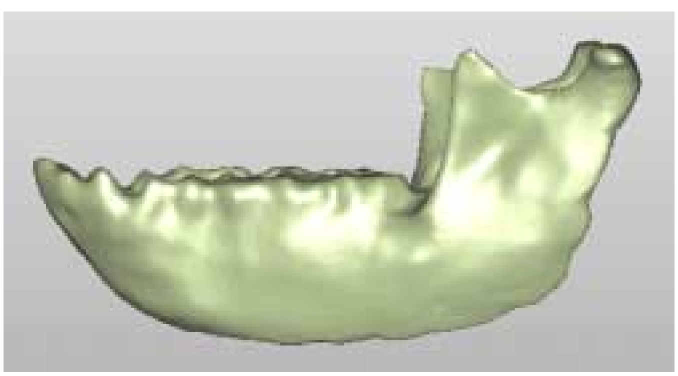

Figure 3. NURBS model of mandible.

(3) A finite element model was built in MSC Patran, a finite element analysis package (**Figure 4**). The imported model was comprised of 410 surfaces and was first converted into a solid model. All the imported surfaces were first connected and shells constructed (collections of connected surfaces). The shells were put together, and a solid is built. A tetrahedral mesh was constructed, and the entire solid was populated with quadratic tetrahedral elements (TET 10).

Each model analyzed had the same geometry and was subjected to the same load and boundary conditions. The differences between the models were the materials properties and how they were assigned.

Several linear stress analyses were performed in which the different models were analyzed. The model was totally constrained at the condyles and angles. Incisal (the right incisor at the front of the jaw) and occlusal (the second molar tooth in the back of the jaw) loads were applied successively to the mandible model to imitate the macromechanical tests conditions.

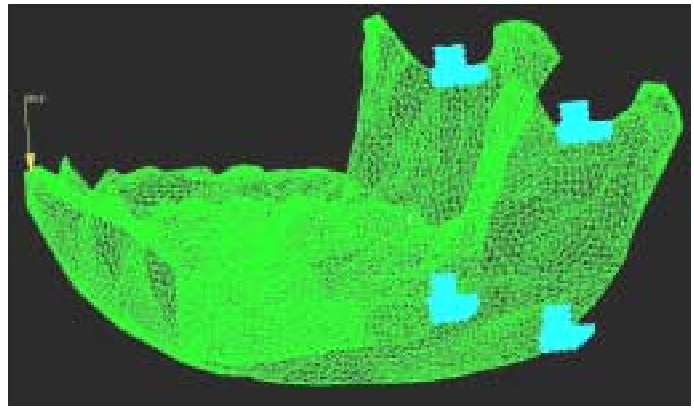

Figure 4. Finite element model.

An isotropic homogeneous model was analyzed to compare the results with those obtained from analyzing the heterogeneous models and with the data from the macromechanical test.

RESULTS

Our preliminary results indicate favorable comparisons with readings from the experimental strains and predictions from our model. Further simulations will be performed to elucidate differences in the mechanical responses of our model assuming various combinations of heterogeneity-homogeneity and anisotropy-isotropy. Of course, characterization of localized strain gradients is highly sensitive to the elastic properties used in the model definition.

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