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Computational modeling of dynamic behaviors of human teeth

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ABSTRACT

Despite the importance of dynamic behaviors of dental and periodontal structures to clinics, the biomechanical roles of anatomic sophistication and material properties in quantification of vibratory characteristics remain under-studied. This paper aimed to generate an anatomically accurate and structurally detailed 3D finite element (FE) maxilla model and explore the dynamic behaviors of human teeth through characterizing the natural frequencies (NFs) and mode shapes. The FE models with different levels of structural integrities and material properties were established to quantify the effects of modeling techniques on the computation of vibratory characteristics. The results showed that the integrity of computational model considerably influences the characterization of vibratory behaviors, as evidenced by declined NFs and perceptibly altered mode shapes resulting from the models with higher degrees of completeness and accuracy. A primary NF of 889 Hz and the corresponding mode shape featuring linguo-buccal vibration of maxillary right 2nd molar were obtained based on the complete maxilla model. It was found that the periodontal ligament (PDL), a connective soft tissue, plays an important role in quantifying NFs. It was also revealed that damping and heterogeneity of materials contribute to the quantification of vibratory characteristics. The study provided important biomechanical insights and clinical references for future studies on dynamic behaviors of dental and periodontal structures.

1. Introduction

Natural frequency (NF) analysis has been widely adopted as a non-invasive and effective method to evaluate periodontal condition, teeth stability and implant osseointegration (Huang et al., 2001, 2005 and, 2006; Lee et al., 2000; Wang et al., 2008; Xin et al., 2009; Shen et al., 2009; Li et al., 2009a, 2009b). It provides an alternative means to the traditional radiographic evaluation that has limitation on biomechanical quantification (Lee et al., 2000; Huang et al., 2001,2006; Xin et al., 2009; Rasmusson et al., 1999). Alveolar bone loss and periodontal attachment decay, as a critical manifesting index of deterioration of periodontal health, can be correlated with noticeable reduction of NF of the periodontal structures (Wang et al., 2008; Shen et al., 2009). The determination of NF of dental tissues or the tissues in the vicinity of dental implants can also help assess the condition of natural tooth and stability of dental implant through follow-up clinical tests or computational bone remodeling simulation (Huang et al., 2005; Li et al., 2009b, 2011, 2010; Rungsiyakull et al., 2014). In addition, a few on-human trials have clinically proved the efficacy of vibration of high frequency and low magnitude on acceleration of orthodontic tooth movement (OTM) (Kau et al., 2010; Leethanakul et al., 2015). This further raises the motivation for improving existing understanding of NF and mode shape associated with dental structures which is far from perfect.

Currently, natural frequencies of teeth, with or without periodontal tissues, are mainly extracted by experiments. Probing methods, conventionally employing impulse hammer, frequency spectrum analyzer and acoustic microphone/accelerometer, have been intensively utilized in the research community (Huang et al., 2001; Lee et al., 2000; Nishimura et al., 2008). However, such approaches may fail to obtain biomechanically accurate vibratory characteristics of tissues of interest even though it contributes towards achieving clinical objectives, e.g. predicting periodontal attachment condition. This is ascribable to the fact that any structure can have multiple natural frequencies and corresponding mode shapes, depending on the material properties, morphology and degree of freedom. The present practical approaches usually target at one particular tooth without comprehending the NFs and mode shapes of the entire structure (Nishimura et al., 2008; Xin et al., 2009; Wang et al., 2008). The frequency where peak or amplified response occurs is approximated to be, or is close to, the resonant frequency. This normally results from superimposing external vibration on its natural frequency profile, whereby this protocol is, in effect, a forced rather than a free vibration. Moreover, the frequency scanning

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interval can be simply too large to capture all natural frequencies experimentally. Despite some clinical data garnered, the characteristics of forced vibration and damping effect can possibly render such experimental approaches incapable of precisely quantifying the dynamic behaviors of dental structures.

Computational methods represented by finite element (FE) techniques were therefore introduced to overcome the above-mentioned technical difficulties and mimic free vibration of periodontal structures (Xin et al., 2009; Wang et al., 2008; Li et al., 2009a; Shen et al., 2009; Li et al., 2014). However, some challenges have to be drawn. Firstly, damping effects of most biological materials, if not all, are difficult to be simulated, which can impose significant influence on dynamic analyses. This as a result, contributes to the major omission of damping effects by most theoretical and FE studies regarding NF extraction on dental or periodontal structures to date (Huang et al., 2005; Wang et al., 2008; Lee et al., 2000, 2009a, 2014). It is even more arduous to measure damping coefficients and factors of structures of human bodies. The periodontal ligament (PDL), acknowledged as a visco-elastic material, can potentially act as a damper during dynamic motion, in spite of the significant difficulty of precisely defining relevant damping coefficients from rather limited references. The damping property should be considered during FEA in which its sensitivity on vibratory characteristics needs to be verified. Secondly, the incorporation of non-linearity of soft tissue, the PDL in this study, can substantially complicate the NF extraction due to the strain/time-dependency of the stiffness. For such non-linear materials, it is theoretically challenging to obtain one or one group of natural frequencies that correspond to one group of mode shapes in the context of different stress states which lead to different extents of deformation and hence varying elastic moduli as the load changes. Thirdly, in most studies, dental bony materials were modeled to be homogeneous while they exhibit site-dependent nature. Accordingly, the effects of incorporation of the heterogeneity need to be examined. Finally, the anatomical inaccuracy of FE models lowered the validity of the results. In literature, most FE studies investigating NF of dental structures used the sectioned models containing single tooth and part of its surrounding tissues (Huang et al., 2005, 2006; Wang et al., 2008; Xin et al., 2009; Shen et al., 2009). It must be pointed out that unlike stress and strain assessments, NF is a global measurement of the dental structure. Such anatomical simplification can considerably alter the overall stiffness, mass and damping characteristics from an intact model. As a result, a collection of natural frequencies and mode shapes of a relatively intact dental model has not been available to date. This paper aimed to address these issues by creating an anatomically accurate and structurally detailed maxilla model for identifying the dynamic behaviors. The influence of introduction of damping effects, heterogeneity and non-linearity of materials on the computation of vibratory characteristics will also be elucidated.

2. Materials and methods

2.1. Theory

The dynamic model can be physically defined as the summation of a series of mass-spring-damper systems, hence consisting of multiple degrees of freedom. The discretization of the system into multiple elemental masses leads to a corresponding number of differential equations of motions, as represented in a matrix form as:

$$(\lambda^2\mathbf{M}+\lambda\mathbf{C}+\mathbf{K})\mathbf{X}=0 \quad (1)$$

where λ denotes the eigenvalue, $\mathbf{X}$ stands for the complex eigenvector and $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ represent mass matrix, damping matrix and stiffness matrix, respectively. In this work, the subspace projection method, a built-in algorithm in Abaqus/Standard (Dassault Systèmes, Waltham, USA), was employed which allowed rapid convergence to the desired eigenvalues for complex NF analysis and eigenvectors for mode shape analysis.

2.2. Maxilla modeling

A human maxilla model was generated based on computerized tomography (CT) images in DICOM format with a resolution of approximately 0.2 mm/pixel. ScanIP 4.3 (Simpleware Ltd., Exeter, UK) was employed for image segmentation (Chen et al., 2015). The resultant maxilla model comprised a full set of maxillary teeth, their adjacent PDLs with thicknesses varying from 0.2 mm to 0.4 mm (Chandra et al., 2007), sectioned alveolar bone and surrounding cortical bone, as

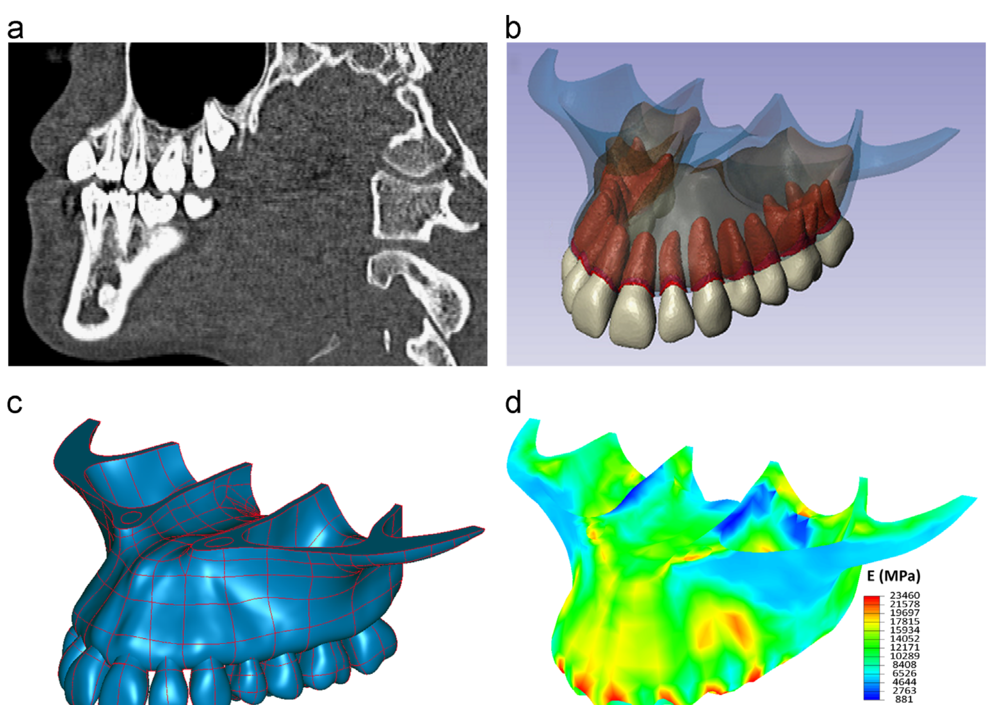

Fig. 1. (a) DICOM images processed in ScanIP; (b) Masks generated for each dental material in ScanIP; (c) NURBS surfaces created in Rhinoceros; (d) Mapping of heterogeneous Young's modulus of bony tissues in Abaqus.