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Finite element simulation of the behavior of the periodontal ligament: A validated nonlinear contact model

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ABSTRACT

Due to its significance in tooth movement, the stress/deformation field of periodontium and the alveolar bone remodeling process, periodontal ligament (PDL) cannot be excluded from the studies investigating dental biomechanics regarding its excessive deformability. Therefore, many analytical and numerical researches are carried out to simulate its response and to create a constitutive model via experiments intending to discover the material properties of PDL. The aim of this study is to formulate a user specified contact model that can be used in conjunction with finite element (FE) software and reflects PDL's influence on neighboring structures based on the currently available information, without requiring an actual volumetric finite element mesh of ligament. The results show good agreement with available experimental tooth mobility data. Smooth stress fields are obtained on the tooth root and alveolar bone, which is a significant aspect in bone-remodeling studies. The advantage of simulating PDL as a contact model at the interface of tooth root and the alveolar process instead of a solid-meshed FE model with poor geometric morphology and/or very dense mesh is expected to save pre/post-processing workforce, to increase the accuracy and to contribute to the smoothness of interface stress distributions.

1. Introduction

Periodontal ligament (PDL) is a soft highly specialized connective tissue which is located between the tooth root and alveolar bone (Berkovitz, 1990; Nyashin and Nyashin, 2000). It is believed that the primary task of this specialized tissue is tooth support (Nyashin and Nyashin, 2000; Natali et al., 2004; Su et al., 2013). Its contribution on tooth movement and stress/deformation field influences the alveolar bone remodeling process since it is the most critical component of periodontium in terms of deformation, hence cannot be disregarded (Nyashin and Nyashin, 2000; Natali et al., 2004; Qian et al., 2009; Wang et al., 2012). Despite its significance, the material properties of ligament are still not clarified (Fill et al., 2011, 2012). However it is well known that the aforementioned functions are fulfilled by simultaneous and/or individual acting of fibrous and the interstitial fluid constituents of ligament (Berkovitz, 1990; Nyashin and Nyashin, 2000; Natali et al., 2004; Qian et al., 2009; Su et al., 2013).

The fibrous constituent is formed basically by collagen fibers in bundles that are attached to tooth root and alveolar bone at respecting ends and comprises 50% of PDL's weight (Berkovitz, 1990; Nyashin and Nyashin, 2000; Naveh et al., 2013). The fiber bundles are dominantly arranged in the direction of principal strains (Black, 1887; Bernick, 1960; Berkovitz et al., 1995), allowing the ligament to resist notable masticatory forces (Natali et al., 2004) through the tensile strength of individual fibers along their axis; a fact which is proved with numerous in vitro experiments performed on bovine, cat, pig and porcine specimens. Regarding those tests, the initial wavy configuration of collagen fibers at unloaded case (Bernick, 1960; Su et al., 2013) is said to yield the nonlinear constitutive behavior under tensile loading. (Dorow et al., 2002, 2003; Natali et al., 2003; Nishihira et al., 2003; Pini et al., 2004; Shibata et al., 2006; Genna et al., 2008; Bergomi et al., 2011). Fiber bundles also contribute to the tooth-support mechanism together with the fluid content when the teeth are exposed to intrusive and extrusive loads (Chiba and Komatsu, 1993; Toms et al., 2002; Sanctuary et al., 2006). In vitro experimental studies performed on transverse sections of an intact tooth with surrounding PDL and bone tissues indicate a nonlinear relation between shear stress and strain as in tensile behavior (Chiba and Komatsu, 1993; Toms et al., 2002; Sanctuary et al., 2006). The existence of high fluid content moving freely within the fiber construction contributes to the compressive resistance of the ligament via reacting to applied loads through hydrostatic pressure (Nyashin and Nyashin,

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2000; Nishihira et al., 2003; Pini et al., 2004; Shibata et al., 2006; Genna et al., 2008; Bergomi et al., 2011). Therefore, at the regions subject to compression, the fiber network becomes sparse and mainly the fluid constituent bears the compressive stresses (Naveh et al., 2013).

As stated by many authors, the behavior of PDL depends not only on the type of loading but also on its rate (Chiba and Komatsu, 1993; Nyashin and Nyashin, 2000; Nishihira et al., 2003). Under high-rate loading, (e.g. 250 N/s is called high-rate in Boldt et al., 2012), fluid constituent in PDL imposes an additional resistance to movement request of tooth. However, as the loading rate decreases, fluid is said to be redistributed in PDL space that result in a decrease of apparent modulus (Nishihira et al., 2003; Bergomi et al., 2011). Such results are indicative responses of viscoelastic nature of PDL tissue (Natali et al., 2004), which is also confirmed by creep and stress relaxation tests performed by various authors (Ross et al., 1976; Picton and Wills, 1978; Walker et al., 1978; Komatsu, 2010; Papadopoulou et al., 2011).

Due to its distinctive influence on tooth mobility besides the stress and deformation distribution on periodontium, studies investigating dental biomechanics under masticatory, traumatic and quasi-static loads, include PDL in finite element models (Aversa et al., 2009; Hohmann et al., 2009; Qian et al., 2009; Groning et al., 2011; Silva et al., 2011; Roscoe et al., 2013; Chen et al., 2014 and many others). All of these studies consider PDL as a 3D body enclosing a tiny and relatively thin volume lying between the tooth and the alveolar bone. Such studies employ many different types of constitutive models ranging from linear elastic to poroviscohyperelastic formulations depending on the complexity possessed (Pietrzak et al., 2002; Natali et al., 2003, 2004, 2011; Pini et al., 2004; Cattaneo et al., 2005; Aversa et al., 2009; Hohmann et al., 2009; Qian et al., 2009; Bergomi et al., 2011; Groning et al., 2011; Silva et al., 2011; Poiate et al., 2011; Fill et al., 2012; Wang et al., 2012; Xia et al., 2012; Papadopoulou et al., 2013; Roscoe et al., 2013; Su et al., 2013). Particularly, bilinear elastic, nonlinear, hyperelastic and viscoelastic models are stated to have better agreement with experimental studies measuring the tooth mobility in increasing order (Parfitt, 1960; Ross et al., 1976). Inclusion of PDL as a 3D body requires a dense FE mesh due to its geometric morphology. This results in large models and time consuming analysis needs, even though in most of the studies; the PDL itself is not the main point of interest to the authors. However, neglecting the ligament oversimplifies the models and yields inaccurate stress and strain distributions on periodontium along with improbable tooth movements as a result of over constrained tooth and pointwise load transfer (Nyashin and Nyashin, 2000; Aversa et al., 2009; Su et al., 2013).

The aim of this research is to propose a contact model between the tooth root and its surrounding alveolar bone to be used in conjunction with finite element programs to reflect the behavior and effects of PDL on teeth movement and alveolar process without utilizing an actual 3D model of PDL. Mechanical behavior and material properties of PDL according to reported analytical, numerical and experimental data are conducted and stress–strain relations are obtained from available test data. Tooth movement under lateral and axial loading conditions are compared to in vivo human experimental studies available, and parameter estimation iterations were performed to the proposed model.

2. Materials and methods

2.1. The geometry

In this study, an abstract three dimensional model of maxilla of a randomly selected patient, containing the right central maxillary incisor and the surrounding alveolar process was used. To create the CAD model; imaging data from a CT scanner (NewTom ConeBeam 3D Imaging, AFP Imaging Corporation, New York) is

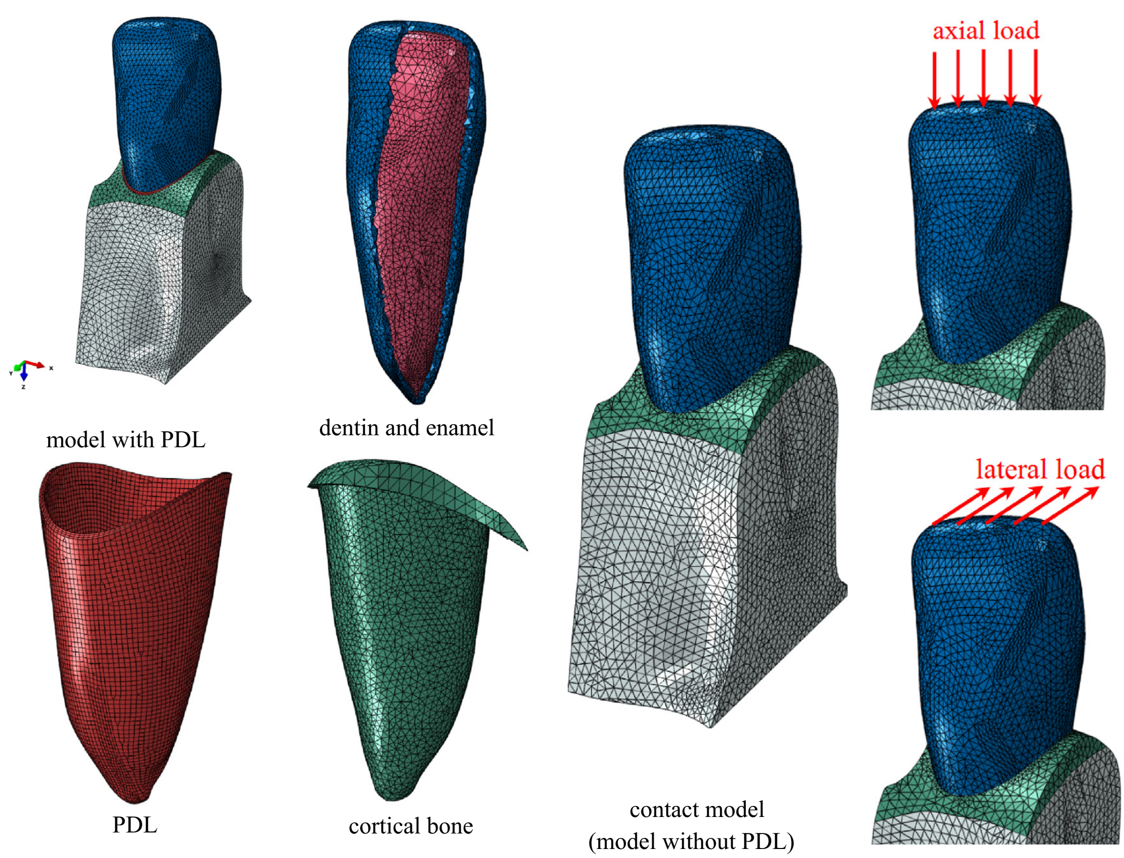

Fig. 1. FE model of central maxillary incisor with and without PDL under intrusive (axial) loading and lateral loading.