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Approach towards the porous fibrous structure of the periodontal ligament using micro-computerized tomography and finite element analysis

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ABSTRACT

The periodontal ligament (PDL) is a porous and fibrous soft tissue situated around the tooth, which plays a key role in the transmission of loads from the tooth to the alveolar bone of the mandible. Although several studies have tried to characterize its mechanical properties, the behaviour of this tissue is not clear yet. In this study, a new simulation methodology based on a material model which considers the contribution of porous and fibrous structure with different material model formulations depending on the effort direction is proposed. The defined material model was characterized by a non-linear approximation of the porous fibrous matrix to experimental results obtained from samples of similar species and was validated by rigorous test simulations under tensile and compressive loads. The global PDL response was also validated using the parameters of the characterization in a finite element model of full human canine tooth obtained by micro-tomography. The results suggest that the porous contribution has high influence during compression because the bulk modulus of the material depends on the ability of interstitial fluid to drain. On the other hand, the collagen fibres running along the load direction are the main responsible of the ligament stiffness during tensile efforts. Thus, a material model with distinct responses depending of the load direction is proposed. Furthermore, the results suggest the importance of considering 3D finite element models based of the real morphology of human PDL for representing the irregular stress distribution caused by the coupling of complex material models and irregular morphologies.

1. Introduction

The periodontal ligament (PDL) plays an important role in transferring loads through the teeth to the alveolar bone (McCormack et al., 2014), and it is the physiological mechanism primarily responsible for tooth movement in response to force. When a tooth is subjected to an excessive force, the strain energy is dissipated by the viscous component of the porous tissue (Komatsu et al., 2007), and the interstitial fluid flows to the alveolar bone which is also a porous medium. Periodontal ligament without diseases contributes to the correct distribution of stresses from the tooth to the alveolar bone (Pihlstrom et al., 2005). However, the periodontal diseases are highly prevalent and could affect up to 90% of the worldwide population (Pihlstrom et al., 2005). Periodontitis, which results in the loss of connective tissue and bone support, is one of the most usual periodontal diseases. It is a major cause of tooth loss in adults (Pihlstrom et al., 2005). It can be ensured that the origin of this disease is multifactorial. Nevertheless, it has been proved (Preshaw et al., 2004) that mechanical loads contribute to the onset of a susceptible host to bacteria proliferation (Pihlstrom et al., 2005).

Biomechanically, the PDL is a kind of composite biological material that can be considered as a porous vasculature solid with a highly structured collagen network (Bergomi et al., 2010). Blood vessels occupy around 4–47% of its volume (Bergomi et al., 2011) containing a fluid (interstitial fluid, blood lymph) (Blaushild et al., 1992; Nyashin et al., 1999). The study of Pini et al. (2004), among others (Komatsu et al., 2007, 2004; McCormack et al., 2014), reveals that collagen fibre density and orientation are primary responsible for the differences observed in PDL mechanical response.

In the late 70 s, different researches started investigating experimentally the mechanical properties of the PDL by in vitro test in small PDL samples (a review of the literature is shown in Table 1). However, quantitative experimental data describing the complete behaviour of the PDL are still unavailable (Fill et al., 2011), as evidenced by the significant discrepancies that exist in published literature regarding mechanical properties of the PDL (Fill et al., 2011). For instance, elastic modulus and Poisson's ratio values can vary between 0.05 (Poppe et al., 2002) to 1 MPa (Jones et al., 2001), and between 0.086 (Bergomi et al.,

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Table 1
Review of published studies including finite element analysis and experimental tests sort by date. Left to right column: tooth that is involved in the analysis; specie; type of computational model; the scan method (if the model is based on real specimen geometry); PDL thickness of the computational model; material model used for the simulation; if experimental analysis is done; if strain rate dependence is analysed; type of loading. (Studies which appear in bold are studies that has been used in this study).

Ref.	Tooth	Specie	Computational model	Scan method	PDL thickness (mm)	Material model (MPa)	Exp. analysis	Velocity depended	Type
(Farah et al., 1973)	First molar	Human	2D	–	Uniform	Linear elastic	No	–	–
(Thresher and Saito, 1973)	First molar	Human	2D	–	Uniform	Linear elastic	No	–	–
(Daly et al., 1974)	Incisor	Human	No	–	Uniform	–	Yes	–	–
(Selna et al., 1975)	–	–	2D – 3D	–	Uniform	Linear elastic	No	–	–
(Widera et al., 1976)	Canine	Human	2D	–	0.4	Linear elastic	No	–	–
(Yettram et al., 1977)	Central incisor	Human	2D	–	Uniform	Linear elastic	No	–	–
(Atkinson and Ralph, 1977)	Various	Human	No	–	–	–	Yes	No	Intrusive test
(Weinstein et al., 1980)	Molar	Canine	2D-3D	–	0.125	Linear elastic	Yes	No	Intrusive test
(Takahashi et al., 1980)	Premolar, molar, incisor	Human	2D	–	0.2	Linear elastic	No	–	–
(Davy et al., 1981)	Central incisor	Human	2D	–	Uniform	Linear elastic	No	–	–
(Atmaram and Mohammed, 1981)	Molar	–	2D	–	Uniform	Linear elastic[a]	No	–	–
(Cook and Weinstein, 1982)	Molar	–	3D	–	Uniform	Linear elastic	No	–	–
(Ferrier and Dillon, 1983)	–	Old pigs	No	–	–	Viscoelastic	Yes	No	Water winding
(Reinhardt et al., 1984)	Central incisor	–	2D	–	Uniform	Linear elastic	No	–	–
(Williams and Edmundson, 1984)	Central incisor	–	2D	–	Uniform	Linear elastic	No	–	–
(Chen and Zhai, 1994)	Premolar	Human	No	–	–	–	Yes	No	Shear
(Tanne et al., 1987)	Premolar	–	3D	–	Uniform	Linear elastic	No	–	–
(Tanne et al., 1988)	Incisor	Animals	3D	–	Non-uniform	Linear elastic	Yes	No	Lateral load
(Farah et al., 1988)	Various	–	2D	–	Uniform	Linear elastic	No	–	–
(van Rossen et al., 1990)	–	–	2D axisymmetric	–	Uniform	Linear elastic	No	–	–
(Andersen et al., 1991)	Molar, first premolar and second premolar	Human	3D	Radiograph	Uniform	Linear elastic	Yes	No	Lateral load
(Cobo et al., 1993)	Canine	Human	3D	Photographs	0.2	Linear elastic	No	–	–
(Chiba and Komatsu, 1993)	Incisor	Rats	–	–	–	–	Yes	Yes	Shear
(Korioth and Hannam, 1994)	All mandible	Human	3D	CT	Non-uniform	Linear elastic (3 sections)	No	–	–
(Komatsu et al., 1996)	Incisor	Rat	–	–	–	–	Yes	Yes	Shear
(Middleton et al., 1996)	Canine	No	2D	–	Uniform	Viscoelastic	No		
(Rees and Jacobsen, 1997)	First premolar	Human	2D	Photographs	0.25	Linear elastic	Yes	No	Lateral load
(Tanne et al., 1998)	Incisor	Human	3D	Anatomic data	–	Linear elastic	Yes	Yes	Lateral load
(Rees, 2001)	Premolar	–	2D	Radiograph	0.3	Linear elastic	No	–	–
(Yoshida et al., 2001)	Incisor	Human	–	–	–	–	Yes	No	Lateral load
(Jones et al., 2001)	Incisor	Human	3D	–	Uniform	Linear elastic	Yes	No	Lateral load
(Qian et al., 2001)	Canine	Dog	3D	–	Non-uniform	Linear elastic[a]	Yes	No	Lateral load
(Poppe et al., 2002)	Incisor and canine	Human	3D	Photographs of sections	Non-uniform	Bilinear	Yes	No	Intrusive load
(Pietrzak et al., 2002)	Incisor	Human	3D	CT	0.2	Nonlinear isotropic	No	–	–
(Toms and Eberhardt, 2003)	Canine	Human	2D axisymmetric	Photograph	0.291	Linear elastic, nonlinear elastic	Yes	No	Shear
(Shimada et al., 2003)	Incisor	Rat	–	–	–	–	Yes	Yes	Intrusive load
(Natali et al., 2008)	–	Pig	–	–	–	–	Yes	Yes	Axial test
(Pini et al., 2004)	Incisor and molar	Bovine	–	–	–	–	Yes	Yes	Axial test
(Cattaneo et al., 2005)	Canine and premolar	Human	3D	μCT	Non-uniform	Nonlinear and linear elastic	No	–	–
(Coelho et al., 2009)	Incisor	Human	2D	–	–	Linear elastic	No	–	–

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