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Biomechanics of a bone–periodontal ligament–tooth fibrous joint

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ABSTRACT

This study investigates bone–tooth association under compression to identify strain amplified sites within the bone–periodontal ligament (PDL)–tooth fibrous joint. Our results indicate that the biomechanical response of the joint is due to a combinatorial response of the constitutive properties of organic, inorganic, and fluid components. Second maxillary molars within intact maxillae ($N=8$) of 5-month-old rats were loaded with a μ-XCT-compatible *in situ* loading device at various permutations of displacement rates (0.2, 0.5, 1.0, 1.5, 2.0 mm/min) and peak reactionary load responses (5, 10, 15, 20 N). Results indicated a nonlinear biomechanical response of the joint, in which the observed reactionary load rates were directly proportional to displacement rates (velocities). No significant differences in peak reactionary load rates at a displacement rate of 0.2 mm/min were observed. However, for displacement rates greater than 0.2 mm/min, an increasing trend in reactionary rate was observed for every peak reactionary load with significant increases at 2.0 mm/min. Regardless of displacement rates, two distinct behaviors were identified with stiffness (S) and reactionary load rate (LR) values at a peak load of 5 N ($S_{5\ N}=290$–523 N/mm) being significantly lower than those at 10 N ($LR_{5\ N}=1$–10 N/s) and higher ($S_{10\ N\text{–}20\ N}=380$–$684$ N/mm; $LR_{10\ N\text{–}20\ N}=1$–$19$ N/s). Digital image correlation revealed the possibility of a screw-like motion of the tooth into the PDL-space, i.e., predominant vertical displacement of 35 μm at 5 N, followed by a slight increase to 40 μm at 10 N and 50 μm at 20 N of the tooth and potential tooth rotation at loads above 10 N. Narrowed and widened PDL spaces as a result of tooth displacement indicated areas of increased apparent strains within the complex. We propose that such highly strained regions are “hot spots” that can potentiate local tissue adaptation under physiological loading and adverse tissue adaptation under pathological loading conditions.

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1. Introduction

The bone–tooth fibrous joint is a dynamic organ that responds to several extrinsic factors to maintain occlusal function (Herring, 2012; Ten Cate, 1998). One prominent extrinsic factor is functional load (Herring, 2012; Popowics et al., 2009). Loads within physiological threshold limits permit soft and hard tissue turnover and maintain optimum periodontal ligament (PDL)-space between the tooth and bone (McCulloch et al., 2000; Niver et al., 2011; Ten Cate, 1998). However, changes in PDL-space can be caused by aberrant loads, eliciting a positive feedback that perpetuates mineral forming and/or resorbing areas in both vascularized bone and cementum. These changes to the adjacent mineralized tissues can increase and/or decrease PDL-space, eventually altering the ability of the PDL to optimally transmit occlusal loads. (Graber and Vanarsdall, 1994; Hurng et al., 2011). As such, mechanical loads on the fibrous joint could induce local strains within the bone-PDL-cementum complex that would generate site-specific physiological changes to maintain the PDL-space or pathological tissue adaptations if loads exceed physiological threshold limits (Bartold, 2012; Wolff, 1986).

Over time, organ-related biomechanics, including tooth deformation, have been investigated using strain gauges (Jantarat et al., 2001; Popowics et al., 2004, 2009), photoelasticity (Asundi and Kishen, 2000, 2001), Moiré interferometry (Wang and Weiner, 1998; Wood et al., 2003), electronic speckle pattern interferometry (Zaslansky et al., 2005, 2006), digital image correlation (DIC) (Qian et al., 2009; Zhang et al., 2009), and *in situ* loading devices coupled to X-ray microscopes (Naveh et al., 2012). However, strain maps using photoelastic, finite element, and numerical

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methods are limited due to assumptions of constitutive properties of tissues and their interfaces (Cattaneo et al., 2005; Komatsu et al., 2004). Among other technique-related problems, Moiré and ESPI are surface-sensitive and do not provide bone-root association unless the organ is sectioned to expose internal structures. In addition, observed PDL mechanics have been predominantly limited to transverse block sections of the bone-PDL-cementum complex (Chiba and Komatsu, 1993; Komatsu et al., 2004). The approach presented in this study exploits technology to date by using a mechanical testing device coupled to a high resolution X-ray microscope (Lin et al., 2012; Naveh et al., 2012) and subsequent use of DIC to identify displacement fields within the bone–tooth fibrous joint.

The objective of this study is to identify the mechanical response of an intact, healthy bone–tooth fibrous joint to simulated compressive loads. Mechanical response of the bone–tooth fibrous joint will be discussed in three steps: (1) mapping the displacement response of the tooth within the alveolar socket in relation to compressive load; (2) correlating the load–displacement curves to the bone–tooth association qualitatively and quantitatively; (3) mapping local displacements within the bone-PDL-cementum complex by digitally correlating 2D virtual sections (2D sections taken from 3D tomographic data sets) at no-load and loaded conditions. This experimental approach allows performing higher resolution imaging without disturbing the loading scheme and the organ. Using DIC as a post processing tool and eliminating the need for sample preparation (Qian et al., 2009; Ziegler et al., 2005) opens a new area of investigation in understanding dynamic processes of different complexes under various loading scenarios (Dickinson et al., 2012; Okotie et al., 2012). Through a hierarchical study from joint function to tissue-level strains, strain concentrated and amplified regions will be identified as "hot spots". By analyzing these hot spots, we can predict dominant tensile, compressive, and/or shear strains within soft and hard tissues, including the PDL-bone and PDL-cementum interfaces of the fibrous joint.

2. Materials and methods

All animal experiments conducted in this study were housed in pathogen-free conditions in compliance with the guidelines of the Institutional Animal Care and Use Committee (IACUC) of UCSF and the National Institutes of Health (NIH). Eight five-month-old male Sprague Dawley rats (Charles River Laboratories, Inc., Wilmington, MA) on a hard-pelleted diet (hard-pellet diet is the normal diet for rats) and bred within a germ-free environment were used. The intact maxillae were freshly harvested after euthanasia and stored in Hank's balanced salt solution (HBSS) with 0.2% sodium azide (Carvalho et al., 1996) for compression tests.

2.1. In situ compression stage

Following specimen preparation (Fig. 1) for compression testing (see Supplemental Information, including Fig. S1, for evaluation of compression stage stiffness), contact with the occlusal composite was ensured by initiating a compression load of 0.2 N. The second molar was loaded at various displacement rates (velocities) of 0.2, 0.5, 1.0, 1.5, and 2.0 mm/min (Hiiemae, 2004; Thomas and Peyton, 1983) until various peak reactionary load responses of 5, 10, 15, and 20 N (Nies and Ro, 2004) were detected by the transducer.

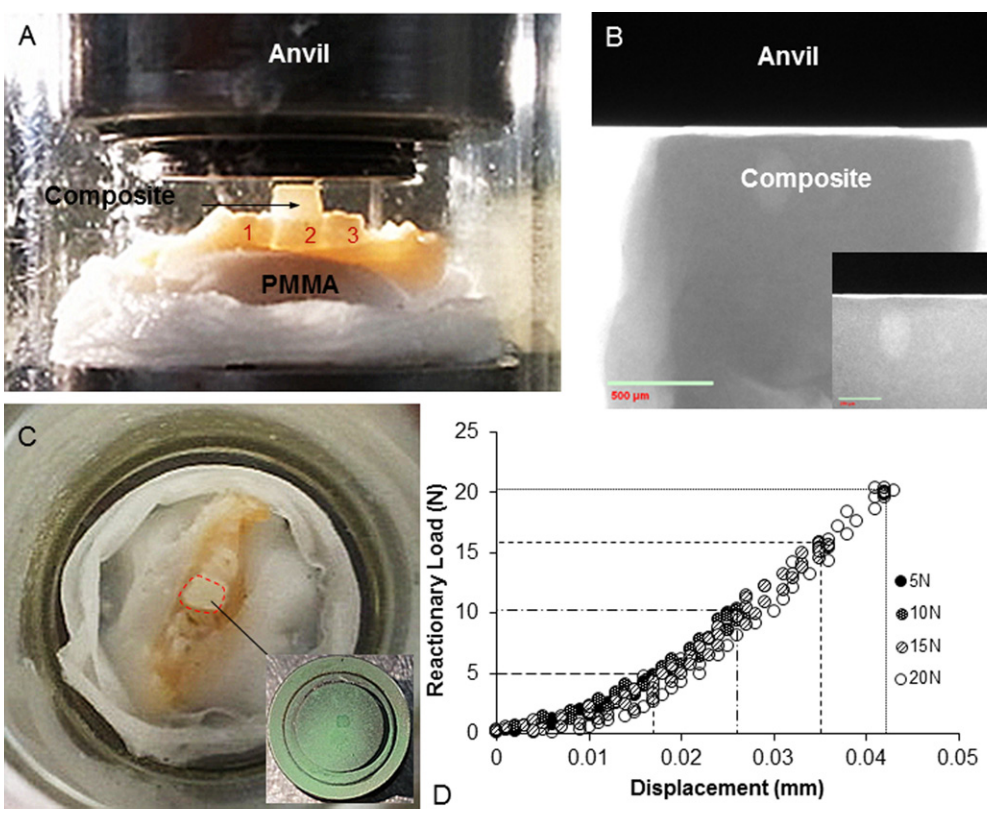

Fig. 1. Specimen preparation for *in situ* mechanical testing. (A) A hemimaxilla secured on to a steel stub with poly(methyl methacrylate) (PMMA) and with an occlusal buildup on the second maxillary molar for uniform compression with an *in situ* loading device. (B) A μ-XCT radiograph shows the relationship of the leveled-composite surface with the opposing anvil (*inset*). (C) Uniform loading on the occlusal build-up is indicated by the contact area marked with ink sprayed on the anvil surface (green, *inset*). (D) A representative output of loading and unloading load–displacement curves for various peak reactionary loads. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)