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Periodontal ligament entheses and their adaptive role in the context of dentoalveolar joint function

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ABSTRACT

Objective. The dynamic bone-periodontal ligament (PDL)-tooth fibrous joint consists of two adaptive functionally graded interfaces (FGI), the PDL-bone and PDL-cementum that respond to mechanical strain transmitted during mastication. In general, from a materials and mechanics perspective, FGI prevent catastrophic failure during prolonged cyclic loading. This review is a discourse of results gathered from literature to illustrate the dynamic adaptive nature of the fibrous joint in response to physiologic and pathologic simulated functions, and experimental tooth movement.

Methods. Historically, studies have investigated soft to hard tissue transitions through analytical techniques that provided insights into structural, biochemical, and mechanical characterization methods. Experimental approaches included two dimensional to three dimensional advanced *in situ* imaging and analytical techniques. These techniques allowed mapping and correlation of deformations to physicochemical and mechanobiological changes within volumes of the complex subjected to concentric and eccentric loading regimes respectively.

Results. Tooth movement is facilitated by mechanobiological activity at the interfaces of the fibrous joint and generates elastic discontinuities at these interfaces in response to eccentric loading. Both concentric and eccentric loads mediated cellular responses to strains, and prompted self-regulating mineral forming and resorbing zones that in turn altered the functional space of the joint.

Significance. A multiscale biomechanics and mechanobiology approach is important for correlating joint function to tissue-level strain-adaptive properties with overall effects on joint form as related to physiologic and pathologic functions. Elucidating the shift in localization of biomolecules specifically at interfaces during development, function, and therapeutic loading of the joint is critical for developing "functional regeneration and adaptation" strategies with an emphasis on restoring physiologic joint function.

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Contents

1. Introduction

The bone-periodontal ligament (PDL)-tooth complex of the oral and craniofacial masticatory complex is a dynamic and biomechanically active fibrous joint [1]. The primary function of the joint is to sustain cyclic chewing forces of varying magnitudes and frequencies. It is categorized as a fibrous joint by virtue of the PDL that (1) serves to attach teeth to the alveolar bone [1], a type of bone that is distinctly different from skeletal bone; (2) serves to consequently facilitate tooth displacement within the alveolar bony socket; (3) serves to distribute and dampen masticatory forces through the vascularized and innervated PDL; (4) contains differentiating zones at the ligament-cementum and ligament-bone entheses (attachment sites) [2,3]; (5) adjoins and interacts with cementum and alveolar bone through ligament-cementum and ligament-bone interfaces; (6) sustains and permits load-based reactionary forces from the tissues (enamel, dentin, cementum) and interfaces (enamel-dentin and cementum-dentin junctions) that makeup teeth exclusively; and (7) subsequently induce mechanical strain not limited to alveolar bone [4,5]. A multitude of structural components and tissues (categorized as biomaterials) join to form this nature's well-lubricated load-bearing joint. Conceivably, this fibrous joint undergoes mechanical strain-mediated adaptation where the measured physical and chemical properties of load-bearing tissues *per se* and their interfaces are appreciated in the context of overall function. Understanding how tooth motion is guided within the alveolar socket in the presence of the PDL, and how the attachment process accommodates cyclic functional loads is critical. This would allow extracting strain-adaptive information that promotes tissue regeneration/remodeling to maintain biomechanical function of a joint.

To date, the biomechanical aspects of the bone-PDL-tooth fibrous joint have been investigated at discrete length-scales, that is, at the levels of the joint [6–13], tissues [3,14–18], and cells [19–29]. Investigations at a joint level have provided insights into the “coupled” nature of joint form and its masticatory function [11]. At a tissue level, biological processes identified as interactions between the soft organic meshwork of the PDL and adjoining hard bone and cementum matrices, and subsequent strain-mediated mineralization of the inorganic hard tissue through active modeling and remodeling [30,31], have provided insights into joint adaptation in response to physiologic and pathologic forces [2,8,9,31–34]. Through a reductionist approach, at a tissue and cellular-level, immunohistological approaches led to mapping of cell behavior and related matrix protein expressions to perturbations placed on tissues and cultured scaffolds [2,3,18,26,28,32,34–36]. This also implies that cell and related tissue mechanics are seldom evaluated within the context of organ function. While probing using reductionist approach answers questions specific to tissues and cells respectively, it minimally addresses the importance of the measured physical and chemical properties, and thereby biological processes within the realm of function. In this manuscript, insights into plasticity and thereby adaptive features within a complex in the context of function will be extracted using principles from biomechanics and mechanobiology. As a result, the manuscript will also highlight an interdisciplinary yet holistic approach (as opposed to reductionist) through the use of various imaging modalities to detail the effect of form and function relationship on strain adaptive properties of human alveolar bone, the PDL, cementum, and PDL-bone and PDL-cementum interfaces. Additionally, results will be discussed in the context of clinically relevant problems specifically related to orthodontics.

The two central objectives to highlight the critical importance of regenerative capacity of PDL-bone and PDL-cementum interfaces within the context of multi-scale biomechanics of the bone-PDL-tooth fibrous joint will be as follows. Within this objective the following salient points will be discussed.

1. The changes in form of a human tooth relative to the socket-shape and *vice versa* can prompt local adaptations through strain concentrations within the PDL, PDL-bone and PDL-cementum interfaces that facilitate the dynamic function of the bone-PDL-tooth fibrous joint [8,31].