

Review Article

Experimentally Determined Mechanical Properties of, and Models for, the Periodontal Ligament: Critical Review of Current Literature

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Introduction. This review is intended to highlight and discuss discrepancies in the literature of the periodontal ligament's (PDL) mechanical properties and the various experimental approaches used to measure them. *Methods.* Searches were performed on biomechanical and orthodontic publications (in databases: Compendex, EMBASE, MEDLINE, PubMed, ScienceDirect, and Scopus). *Results.* The review revealed that significant variations exist, some on the order of six orders of magnitude, in the PDL's elastic constants and mechanical properties. Possible explanations may be attributable to different experimental approaches and assumptions. *Conclusions.* The discrepancies highlight the need for further research into PDL properties under various clinical and experimental loading conditions. Better understanding of the PDL's biomechanical behavior under physiologic and traumatic loading conditions might enhance the understanding of the PDL's biologic reaction in health and disease. Providing a greater insight into the response of the PDL would be instrumental to orthodontists and engineers for designing more predictable, and therefore more efficacious, orthodontic appliances.

1. Introduction

Clinical orthodontic treatment is a lengthy, iterative, and possibly inefficient process [1]. Force systems in most orthodontic treatments are considered indeterminate and the magnitude of forces and moments are, in practice, largely unknown [2]. Furthermore, biologic response to orthodontic forces is not well understood. The physiological mechanism primarily responsible for tooth movement in response to a force is the periodontal ligament (PDL) [3]. Short-term tooth movement is regarded as primarily governed by PDL deformation because teeth are virtually rigid and are connected to an almost as rigid mandible by the PDL [4].

From a biomaterials perspective, the PDL is a complex, fiber-reinforced substance that responds to force in a viscoelastic and nonlinear manner [5]. The PDL consists of 53–74% collagen fibers and 1–2% blood vessels and

nerve endings that are embedded into an amorphous mucopolysaccharide matrix [6, 7]. Fibrous collagen elements resist tensile forces and the highly hydrated viscous ground substance into which fibrous proteins are embedded forms the extracellular matrix. The ground substance is responsible for the PDL's viscoelastic properties when subject to loading [8]. Also, the PDL's cellular response to mechanical loading results in a metabolic response (remodeling of the ground substance and fibrous tissue) [7].

Orthodontic tooth movement is thought to require a minimum of four to eight hours [3] duration of force application and has been shown to be optimal when approximately continuous forces are applied [9–11]. The PDL's response is characterized by instantaneous displacement, followed by a more gradual (creep) displacement that reaches a maximum after five hours [12], suggesting that fluid bound within the PDL may play an important role in the transmission, and damping of forces acting on teeth.

PDL steady-state elastic response is usually attained about five hours after the teeth are loaded—when the flow of the PDL's interstitial fluid through the surrounding alveolar bone causes the pressure within the PDL to decrease and the solid phase to carry the load alone [12]. Similar results were described in earlier experimental studies in which teeth were loaded laterally [13, 14], and teeth subjected to an intrusive [15–17], and/or an extrusive [18] load. Further, the tissue responds rigidly to rapid deformations (mastication) [19] while deforming elastoplastically when subjected to low-grade continuous forces (orthodontic movements) [20].

Biomechanical analyses of not only PDL stress-strain responses, but also viscoelastic responses such as hysteresis, creep, and stress-relaxation, help elucidate the tooth support function of the tissue [21]. Viscoelastic responses are principal causes of energy dissipation [22]. Without strain energy dissipation, excessive energy may cause tissue breakage [23–27]. Therefore, it seems highly probable that viscoelasticity is important for the tooth support function of the PDL, but little is known about the relation between the viscoelastic response and structure of the PDL [28].

Thus, the PDL's mechanical properties are essential parameters for understanding the mechanical behavior of a tooth root and surrounding tissues [4]. These properties are important to orthodontic biomechanics, since its main focus is to understand how forces, which are applied to the tooth crown by means of elastic deformation of metal wires, are transferred to a tooth root and surrounding tissues.

Although much is known about the mechanical properties of teeth and alveolar bone, there is no similar definitive knowledge about the PDL [4]. Unfortunately, quantitative experimental data describing the complete behavior of the PDL are unavailable [29]. Determining stress levels in different areas of the PDL, which are the most important and least understood stress-strain levels in orthodontic biomechanics, may offer the best means of correlating the application of force on a tooth with the tooth's response [3, 30].

The objective of this paper is to highlight and discuss the discrepancies that exist in published literature regarding experimentally determined mechanical properties of the PDL.

2. Materials and Methods

Articles were identified by searches of the following databases: Compendex, EMBASE, MEDLINE, PubMed, ScienceDirect, and Scopus, starting from the early 1900s through August 2010 in the English language (citations of publications in other languages were included, but these were sourced from English publications). We used the following search terms: “biomechanics,” “elasticity,” “finite element analysis,” “finite element method,” “mechanical properties,” “nonlinear elasticity,” “orthodontic tooth movement,” “periodontal ligament (PDL),” and “viscoelastic.”

3. Results

3.1. Mechanical Properties of the PDL. To date, there has been considerable research on the PDL given its crucial role in tooth movement and bone remodelling [31, 32]; much of which has been on determining PDL mechanical properties. Histological periodontal tissue changes during experimental tooth movement have been fervently investigated [33–35]. The PDL's biological reaction is determined by stress-strain levels induced by mechanical forces applied to the tooth [36–40]. Young's (elastic) modulus of the PDL appears to be the most important determinant for instantaneous tooth displacement [41]. However, lack of PDL's mechanical properties consistency throughout the literature is a function of several, often interrelated, parameters. Difficulty lies in directly obtaining PDL data because tooth movement greatly depends on tooth size/shape [4] and, likely as with similar tissues, on strain rate [42].

3.2. Experimental Research and Results. Differences in PDL material properties and experimental approaches obviate the need for a consistent, standard protocol for testing and modeling the PDL. Elastic modulus was found to range from 0.01 to 1750 MPa, and Poisson's ratio ranged from 0.28 to 0.49. Table 1 summarizes reported PDL material properties (does not include some studies that reference previously reported values)—highlighting the variability existing throughout the literature.

Experimental approaches for determining PDL material properties are summarized in Table 2. Diversity in experimental approaches is a cause of the wide dispersion of results when investigating PDL behavior, obviating the need for a standardized testing protocol. However, extracting small samples with a regular geometry from a complex biological structure is an arduous task.

The results show that regardless of the approach/methodology utilized (i.e., 2D-FEM, experimental, 3D-FEM, etc.), there is no conclusive correlation or relationship between the reported material parameters of the PDL and the experimental method that was used to obtain them. In fact, there exists such variability in these parameters that it may be a possibility that each individual PDL (i.e., from every single tooth) has its own distinct biomechanical behaviour—much like the uniqueness of a fingerprint. This could potentially be an area, not considered before, that calls for further work and investigation. It may be that a single, all-encompassing, PDL behavioural model is not the appropriate approach in understanding and predicting orthodontic tooth movement.

The results, similar to those found in Table 1, show that regardless of the methodology (i.e., *in vivo* or *in vitro*) numerous varying individual factors may impact the PDL's biomechanical response. Thus, a similar conclusion presents itself—a single, all-encompassing, PDL behavioural model may not be the appropriate approach in understanding and predicting orthodontic tooth movement. In addition, for researchers performing further investigation into the PDL's material properties, the results raise an awareness of what may influence their results.

TABLE 1: Material properties of the PDL.

Reference	Year	Young's modulus (MPa)	Poisson's ratio	Species	Tooth	Method
Yamanda and Evans [43]	1970	1.4	—	Human	All teeth	Experimental
Atkinson and Ralph [44]	1977	3.8	—	Human	Lower premolar	Experimental
Mandel et al. [45]	1986	3	—	Human	Lower premolar	Experimental
Thresher and Saito [46]	1973	1379	0.45	Human	Upper incisor	2D-FEM
Wright [47]	1975	49	0.45	Human	All teeth	2D-FEM
Wider et al. [48]	1976	68.9	0.45	Human	Molar	2D-FEM
Yettram et al. [49]	1977	0.18	0.49	Human	Upper incisor	2D-FEM
Takahashi et al. [50]	1980	9.8	0.45	Human	Lower teeth	2D-FEM
Atmaram and Mohammed [51]	1981	175–350 ⁱ	0.45	Human	Molar	2D-FEM
Siegele et al. [52]	1986	0.26, 8.5 ⁱ	0.28	Human	Upper incisor	2D-FEM
Farah et al. [53]	1988	6.9	0.45	Human	Lower molar	2D-FEM
Ko et al. [54]	1992	68.9	0.45	Human	Upper incisor	2D-FEM
Middleton et al. [55]	1996	0.75–1.5 ⁱ	0.45	Human	Canine	2D-FEM
Weinstein et al. [56]	1980	68.9	0.45	Human	Lower premolar	3D-FEM
Tanne et al. [57]	1987	0.69	0.49	Human	Lower premolar	3D-FEM
Goel et al. [58]	1992	1750	0.49	Human	Lower premolar	3D-FEM
Korioth and Hannam [59]	1994	2.5–3.2	0.45	Human	Lower teeth	3D-FEM
Pietrzak et al. [6]	2002	0.010–0.031 ⁱⁱ	0.45–0.49	Human	Upper incisor	3D-FEM
Rees and Jacobsen [60]	1997	50	0.49	Human	Lower premolar	Exp/2D-FEM
Cook et al. [61]	1982	68.9	0.45	Dog	Upper premolar	Exp/3D-FEM
Andersen et al. [62]	1991	0.08–68.9 ⁱⁱ	0.30–0.49	Human	Lower premolar	Exp/3D-FEM
Tanne et al. [41]	1998	0.667	0.49	Human	Upper incisor	Exp/3D-FEM
Siebers [63]	1999	0.05, 0.22 ⁱⁱⁱ	0.3	Pig	Canine	Exp/3D-FEM
Jones et al. [64]	2001	1	0.45	Human	Upper incisor	Exp/3D-FEM
Qian et al. [65]	2001	2, 10–90 ⁱⁱⁱ	0.3	Dog	Canine	Exp/3D-FEM
Yoshida et al. [66]	2001	0.25–0.96 ⁱⁱ	0.45	Human	Upper incisor	Exp/3D-FEM
Poppe et al. [67]	2002	0.05, 0.28 ⁱⁱⁱ	0.30	Human	Incisors, canines	Exp/3D-FEM
Cattaneo et al. [68]	2005	0.07, 0.044, 8.5	0.45	Human	Lower teeth	Exp/3D-FEM
Li et al. [69]	2006	6.89	0.45	Human	Incisor	Exp/3D-FEM
Gonzales et al. [70]	2009	0.7	0.49	Rat	Upper molar	Exp/3D-FEM
Meyer et al. [71]	2010	0.5 (matrix), 10 (PDL)	0.47, 0.35	Dog	Central incisor	Exp/3D-FEM

ⁱCalculation performed with two types of PDL elements.

ⁱⁱCalculations performed using various values of Young's modulus.

ⁱⁱⁱCalculations performed using a bilinear behaviour of Young's modulus.

4. Discussion

The discrepancy and inconsistency of elastic constants for the PDL was evident from the literature. These variations were due to a myriad of factors including experimental protocol inconsistencies. Experimental studies on tooth movement are difficult to interpret because the description of orthodontic forces is not uniform and is incomplete [72]. Pini et al. [73] indicated that the stress-strain curves from their experiments showed that the PDL is characterized by time-dependent, nonlinear mechanical behavior with the typical features of collagenous soft tissues.

When applying an orthodontic force to a tooth, the generally accepted concept is that bone resorption occurs on the PDL's compressed side, and bone apposition occurs on the tensed side. A widening of the PDL space follows and then a tooth migration towards the compressed side [74].

The external stresses and strains the PDL is subjected to are integral stimuli for alveolar bone remodeling. However, Cattaneo et al. [68] showed that loading of the periodontium cannot be explained in simple terms of compression and tension along loading direction. It was observed that tension in the alveolar bone was far more predominant than compression. Furthermore, Meikle [75] indicated that firmly embedded in the orthodontic subconscious was the idea that pressure and tension sites were generated within the PDL, but he believed there were two major conceptual problems with this hypothesis; based on experimental evidence [76], it was unlikely that PDL principal fibers underwent significant tensile strain, or transferred forces directly to the alveolar bone. Conversely, he supported the idea that tooth movement experiments [77] seemed to corroborate the hypothesis that differential pressures can be generated within the periodontium.

TABLE 2: Experimental approaches in PDL research.

Reference	Year	Species	Method	Factors impacting PDL response
Reitan [33, 72]	1957 1964	Human	<i>in vitro</i>	Applied force magnitude and type (continuous versus intermittent), mechanics involved (tipping versus bodily movement), and individual patient variation in tissue reaction
Reitan [78]	1967	Human	<i>in vitro</i>	Density, supraalveolar fibers, structure of collagen fibers and cellular activity in the PDL. Force/unit of root surface area (on response rate)
Mitchell et al. [79]	1973	Cat	<i>in vitro</i>	Individual tooth types
Chiba et al. [80]	1981	Rat	<i>in vitro</i>	Adrenocorticoids (drug)
Ohshima [81]	1982	Rat	<i>in vitro</i>	Lathyrogens (drug)
Komatsu et al. [82]	1988	Rat	<i>in vitro</i>	Occlusal conditions
Ashizawa and Sahara [83]	1998	Rat	<i>in vitro</i>	Stress found to vary significantly in different segments and PDL thickness also changed with the remodeling of the alveolar bone during treatment
Toms et al. [84]	2002	Human	<i>in vitro</i>	Age, disease state (health), anatomical location of tooth root, teeth (premolar, canine, incisor), arch (maxillary, mandibular) and fiber orientations
Dorow et al. [85]	2003	Pig	<i>in vitro</i>	Young's modulus depended on loading velocity. This meant stiffness of the PDL increased with loading velocity—conforming to studies [86–88]
Kawarizadeh et al. [89]	2003	Rat	<i>in vitro</i>	Fresh versus frozen specimens
Komatsu et al. [28]	2004	Rat	<i>in vitro</i>	Advancing age enhanced PDL's mechanical strength and toughness (mostly incisal region) and decreased viscous fraction (incisal and basal regions) along the incisor's long axis
Komatsu et al. [90]	2004	Rat	<i>in vitro</i>	Maximum shear stress and stiffness decreased with age; toughness unchanged (>extensibility).
Sanctuary et al. [25]	2005	Cow	<i>in vitro</i>	Species, location, strain history, and strain rate. Strain rate was also suggested by Natali et al [91]
Tanaka et al. [92]	2007	Pig	<i>in vitro</i>	Preparation of specimens and location in mouth. Nonlinearities, compression/shear coupling, and intrinsic viscoelasticity affected shear material behaviour (important implications for load transmission from tooth to bone and vice versa)
Genna et al. [93]	2008	Pig	<i>in vitro</i>	PDL's small size and complex microstructure; PDL sample preparation, sample cutting, with associated damage to inclined fibres; sample freezing; presence/absence of pressurized fluids during tests; difference in results taken from different teeth or root positions along the same tooth; sample orientation and fibre inclination
Qian et al. [94]	2009	Pig	<i>in vitro</i>	Deformation patterns in entire periodontium depended on geometrical profiles and material properties—especially PDL.
Pilon et al. [95]	1996	Dog	<i>in vivo</i>	Differences in bone density, bone metabolism, and turnover in the PDL. Force magnitude was NOT decisive in determining the rate of bodily tooth movement

TABLE 2: Continued.

Reference	Year	Species	Method	Factors impacting PDL response
Komatsu et al. [96]	1998	Hamster Mouse Rabbit Rat	<i>in vivo</i>	Species, strength, and stiffness of the periodontal collagen fibers and PDL waviness and thickness depended on developmental stages of the periodontal collagen fibers possibly related to the general arrangement, diameters and collagen fiber bundle densities, and fiber insertions into the alveolar bone and cementum. Dynamic shear moduli increased nonlinearly with frequency—regardless of the magnitude of applied strain (implies that PDL stiffness increases with frequency)
Tanne et al. [41]	1998	Human	<i>in vivo</i>	Adult Young's modulus (PDL) was greater than that of adolescents. [97, 98] showed similar results. This might lead to delay in adult tooth movement from a reduction in the PDL's biological response
Jones et al. [64]	2001	Human	<i>in vivo</i>	Age and periodontal health
Yoshida et al. [66]	2001	Human	<i>in vivo</i>	Load magnitude

TABLE 3: Factors affecting the PDL's mechanical properties.

Factor	Specifics
Geometric configuration of the periodontium	N/A
Size and shape of tooth root	Bicuspid, canine, molar, and so forth
Region of the PDL	Regional differences and thickness
Physiological	Age, ethnicity, race, gender, and genetics
Environment	Dental and overall physical health, diet
Type of loading	Loading frequency, strain rate, loading velocity, and load direction
Material mechanics	Nonlinearities, compression/shear coupling, and intrinsic viscoelasticity

Pietrzak et al. [6] indicated that reliable values of the PDL's material properties were lacking, specifically noting the significant variance in Young's modulus. They also pointed out the dearth of experimental evidence to justify the common assumption of PDL incompressibility, since it is extremely complicated and difficult to conduct accurate and reproducible experiments on thin, soft, and delicate PDL tissue.

Tanaka et al. [92] pointed out that some previous experiments [28, 90] examined the PDL's viscoelastic behavior with quasistatic experimental setups. However, the quasistatic model is only an abstraction as it was found to work reasonably well for soft tissues, but even so, only for certain ranges of stresses, (rates of) strains, and frequencies of oscillations in which the formula (model) does not represent a specific tissue accurately [42]. A quasistatic viscoelastic response corresponds to stress relaxation and creep testing in terms of PDL experimentation. Damping is not modeled effectively and can be problematic when investigating the strain rate effect.

4.1. Factors Affecting Behavior. Considerable variation in PDL tissue response to tooth movement has been reported [99], and it results from differences in biomechanical signals

and also to specific host differences, such as diurnal rhythms [100], occlusion [101], systemic metabolism [102], age [74, 103, 104], or normal variation in bony trabeculation. Since the PDL is viscoelastic [27, 73, 85, 105–108], its properties can vary with the mode of loading [109] and species type [96].

Iwasaki et al. [110] stated that the speed of orthodontic tooth movement was a function of environment, genotype, and genotype environment. Specific examples include:

environment—orthodontic treatment, plaque, smoking status, drug use, disease, and diet;

genotype—simple (single) or complex (multiple) gene interaction(s);

genotype-environment—ageing, behavior, lifestyle, education, and socioeconomic status.

Various authors [16, 85, 86, 111–113] have demonstrated the nonlinearity and time dependence of the relationship between load and tooth displacement through *in vivo* experiments. Other studies [28, 66, 90] described the PDL as nonlinear and segmentspecific (viscoelastic properties could be assumed to differ locally and be dependent on the magnitude and frequency of the loads applied).

Genna et al. [93] pointed out that there was an effect associated with freezing collagen that must be accounted for in PDL models. Recently, Bergomi et al. [20] concluded that (i) the PDL showed pseudo-plastic viscous features for cyclic compressive loading, and (ii) these viscous features essentially resulted from interactions between the porous matrix and the unbound fluid content of the tissue.

4.2. Summary of Factors. A summary of the factors that may affect the mechanical properties of the PDL is shown in Table 3. However, a clear separation in the importance and a definitive measure of the degree of influence of these factors was absent from the literature.

Most experimental research focused on determining single-factor effects on the PDL (i.e., differences in tooth movement based on the size/shape of the tooth) and, thus, no inference or distinction can be stated with a reasonable degree of confidence on the combined effect of several factors.

The degree of importance or level of error of the factors could not be ascertained from the literature. Therefore, possible future research could be to examine the effect that various parameters/factors have on the PDL's biomechanical properties and then quantitatively determine the degree of influence of each factor on the PDL's response.

Considering the gamut of data and the sporadic nature of experimental results, taken together with the uniqueness of the PDL's biomechanical properties, it can be concluded that the research focus should be placed on human PDL biomechanics and the impact of individual factors to the material properties. Future research should gravitate towards delineating the relative contributions of each individual factor in order to increase model accuracy and to tailor clinical treatment to be as patient specific as possible. In terms of modeling, it is believed that the most appropriate approach is to use a combined 3D FEM and experimental methodology in order to ensure a reasonably accurate fit. As a first step, the research should, however, focus on the development of a preliminary model that allows for a better phenomenological description of PDL behaviour under static, near clinical, orthodontic loading conditions.

5. Conclusion

The gamut of experimental approaches and simplistic/inaccurate assumptions highlight the need for continued research in ascertaining PDL properties under various and well-defined loading conditions, both clinical and experimental. These inconsistent properties underlying the PDL knowledge base are due, in part, to difficulties in examining this thin tissue and variations in experimentation approaches. It was shown that there were significant variations, some on the order of six orders of magnitude, of the elastic constants and mechanical properties of the PDL.

A better understanding of the PDL's biomechanical behavior under physiologic and traumatic loading conditions might enhance the understanding of its biologic reaction in health and disease [114]. By providing a greater insight into human dental tissue response, we can help

orthodontists improve people's health, appearance, and self-confidence.

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