Holistic force-displacement behavior of porcine periodontal ligament—numerical simulation and in-vitro experiment

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Abstract

In recent years, orthodontic treatments have become increasingly popular. In these treatments, orthodontic forces, which cause the absorption and deposition of alveolar bone, are applied through brackets and teeth in order to move the teeth to the expected position. The periodontal ligament (PDL) has a determinative role in dental biomechanics; however, the difficulty of predicting PDL behavior has limited the advancement of dental biomechanics. Therefore, this study intends to measure the biomechanical behavior of the PDL and then develop an analytical model to predict the holistic force-displacement relationship of the tooth. In this study, a porcine premolar, including the tooth, periodontal ligament, and alveolar bone, was harvested for experimental purposes. A custom-made apparatus was designed to measure the force-displacement relationship of the PDL. Three analytical models, including linear, exponential, and power functions, were adapted to fit the experimental results. In addition, three-dimensional finite element models were constructed from micro-CT sectional images, and the hyperelastic behavior (Mooney-Rilvin equation) of the PDL was simulated. The results showed that the PDL exhibited nonlinear biomechanical behavior. The power function was found to be a good fit for the force-displacement relationship of the PDL. Furthermore, it was found that the hyperelastic model could predict the biomechanical behavior of the PDL for tension less and equal to 20 N.

Key words: Periodontal ligament, Force-displacement behavior, Analytical model, Hyperelastic, Finite element analysis

1. Introduction

The physiological mechanism of tooth movement is a crucial issue in dental treatment, especially in orthodontics; it is a consecutive and time-consuming process of gradually moving teeth into position (Proffit et al., 2014). The periodontal ligament (PDL) plays a determinative role in dental biomechanics; it is located between the tooth and alveolar bone and absorbs the occlusal impact load and the formation and resorption of the alveolar bone for tooth movement. Therefore, understanding the biomechanical behavior of the PDL is essential in orthodontics, prosthodontics, and other dental research.

However, while the biomechanics of the PDL are important, the behavior remains unclear. In some research, the force-displacement relationship has been investigated using harvested animal specimens. Schrock et al. recorded the force-displacement relationships of thick slice samples from the incisors of a horse (Schrock et al., 2013). Pini et al. reported the mechanical response of the PDL, which was obtained from different portions of bovine incisors and molars when they were subjected to uniaxial tension and compression (Pini et al., 2004). In other research, a laser-optical system was designed to verify the behavior of porcine teeth and the existence of hysteresis under different strain rates was reported (Dorow et al., 2002, 2003; Natali et al., 2007). Although the sliced samples were taken from part of a tooth, the results of these studies reflect the typically non-linear behavior of the partial PDL, but may not be representative for the entire PDL.

Understanding the kinetics of natural teeth under physiological loading is a fundamental issue in dentistry because
this knowledge could help to design better dental prostheses and implants. Boldt et al. developed an optical system to measure the \textit{in vivo} force-displacement relationship of the human incisor (Boldt et al., 2012), and their results showed that lateral forces caused greater displacement than axial forces when applied to the incisor. Nevertheless, various loading patterns should be investigated to better understand the biomechanical characteristics of the PDL.

Most \textit{in vitro} biomechanical experiments of the PDL were not set up to holistically evaluating the stress-strain relationships and cannot be prevented from a destructive approach. Hence, analytical models have become effective alternatives for estimating the biomechanical behavior of the PDL. Many researchers have identified the nonlinear behavior of the PDL, including the viscoelasticity (Kawarizadeh et al., 2003; Komatsu et al., 2004; Natali et al., 2004; Poppe et al., 2002; Qian et al., 2009; van Driel et al., 2000; Ziegler et al., 2005). Due to the complexity of the physiological structure and the feasibility of the measuring modality, the difficulty of predicting the behavior of the PDL has limited the advancement of dental biomechanics. Therefore, this study intends to measure the biomechanical behavior of the PDL and develop an analytical model to predict the holistic force-displacement relationship of the tooth.

2. Materials and Methods

2.1 Experiment

To perform the biomechanical tests, five porcine premolar teeth were harvested from which the surrounding gingiva and mucosa were removed. Each specimen included the premolar tooth, PDL, and alveolar bone. The crown and alveolar bone were then perforated with a 3 mm hole before being mounted in a custom-made apparatus (Fig. 1). The main components of the apparatus included a micrometer (Model No. 103-137, Mitutoyo Corporation., Japan) with a resolution of 0.01 mm to move the sample jig, a load cell (MDB-50; Transducer Techniques, CA, USA) to record the applied force, a bi-directional linear motion rolling guide (IKO LWL9 B; Nippon Thompson Co., Ltd., Japan) to ensure that only tensile or compressive forces were applied to the specimen, a linear variable differential transformer (LVDT, DTH-A-10, Kyowa Electronic Instruments Co., Japan) to measure the displacement of the tooth, and a sample holder to hold the specimen while it was subjected to the applied force.

![Fig. 1 Custom-made apparatus: (A) micrometer; (B) load cell; (C) linear motion rolling guide; (D) LVDT; (E) sample holder.](image1)

The premolar was preloaded with a tension of 1 N before the test began. Then, a 5-N tensile force was applied to the premolar and maintained for 1 min while the displacement was recorded by the LVDT. The premolar was then unloaded and allowed to rest for 5 min so that it would recover to its original status. This procedure was repeated for five times and the average displacement was calculated. Using this protocol, 10, 20, 40, and 60-N tensile forces were also tested and the force-displacement relationships were obtained. In this study, three empirical models, namely exponential, and power functions, were adopted to fit the force-displacement data.

2.2 Finite element analysis

The premolar used to create the finite element (FE) model was randomly selected from among all specimens, and sectional images were scanned by a micro-CT (SkyScan 1076; Bruker-MicroCT, Belgium) to generate the geometric model. The parameters of the micro-CT were 70 kV, 100 μA, 35 μm resolution, and 316 ms exposure time. A
three-dimensional mesh model of the porcine premolar was then generated using the FE package (ANSYS; ANSYS, Inc., Canonsburg, PA, USA). A 10-node tetrahedral element was used with an element size of 0.4 mm in the PDL and 0.6 mm in the tooth and alveolar bone. These parameters were selected based on the results of a convergence test prior to the analysis.

In consideration of the computing time, the mechanical properties of the tooth (E = 22000 MPa; ν = 0.3) and alveolar bone (E = 1200 MPa; ν = 0.3) were assumed to be linear elastic and isotropic. The PDL was assumed to be hyperelastic (i.e., a 3-parameter Mooney–Rivlin model) in which \( C_{10}, C_{01}, \) and \( C_{11} \) are the material constants and \( \delta \) is the material incompressibility parameter, \( I_1 \) and \( I_2 \) are the first and second deviatoric strain invariants, and \( J \) can be thought of as the ratios of the deformed to undeformed volumes of material. The strain energy density function \( W \) is given by:

\[
W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + \frac{1}{\delta}(J - 1)^2
\]

The nodes on the perforated hole of the alveolar bone were fixed as the boundary condition, and the magnitude of the axial tensile force applied to the hole of the premolar was experimentally determined (Fig. 2). The displacements obtained from the finite element simulations were compared with those from the experiments and the empirical models.

Fig. 2 FE model used in this study: (a) each part of the tooth specimen (grey: premolar; pink: the periodontal ligament; orange: alveolar bone); and (b) the loading and boundary conditions.

Fig. 3 The force-displacement data obtained from the creep experiments.
3. Results

The experimental results of the tensile test are shown in Fig. 3. The force-displacement relationship of the PDL exhibited nonlinear behavior and clearly varied between the samples as the applied force increased. The curve fitting results of the analytical model and experiment are shown in Fig. 4. The coefficients of determination revealed that the power function provided the best fit to the experimental results.

The material constants $C_{10}$, $C_{01}$, $C_{11}$, and $d$ were obtained after a trial-and-error FE analysis to approximate the force-displacement relationship from the experiment. Through the trial-and-error process, we found that the constants $C_{11}$ and $d$ had a greater effect on the biomechanical properties of the PDL. Finally, the values of the material constants were determined to be: $C_{10} = 0.005$ MPa; $C_{01} = 0.005$ MPa; $C_{11} = 0.1$ MPa; and $d = 4$.

4. Discussion

The purpose of this study was to determine the force-displacement relationship of the porcine PDL and establish a suitable constitutive equation of the PDL. In addition, a hyperelastic model was developed to simulate the behavior of the PDL. Many studies have investigated the biomechanical behavior of the PDL by using specimens from various animals, such as rats, rabbits, and pigs (Dorow et al., 2002; Kawarizadeh et al., 2003; Komatsu and Chiba, 2001; Komatsu et al., 2004; Natali et al., 2007). Animal models such as these have become viable alternatives when studying the biomechanics of the PDL because it is difficult to obtain complete human tooth samples. Nevertheless, the mechanical properties of the PDL are species dependent. Porcine samples are a viable alternative for biomechanical studies because pigs have similar dietary habits to those of humans, although the deviation of the tooth morphology between pigs and human beings is still an issue.

Based on the results of our study, the power function fitted the experimental measurements better than did the linear and exponential functions with higher coefficient of determination ($R^2 = 0.933$). Because the experimental results showed that the stiffness increased greatly when the tensile forces were more than 20 N, the exponential and power functions were selected as the equations used in the analytical model. Even though the PDL was found to exhibit nonlinear behavior, the linear function was still adopted because of its simplicity. We also found that the use of the linear model provided a better representation of the biomechanical behavior of the PDL than did the exponential model. From this, we inferred that the large deviation of the displacement observed when the applied force was over 20 N caused the nonlinearity of the force-displacement relationship to be less remarkable. The establishment of an appropriate analytical model could provide clinical dentists a convenient approach to predict the final results of orthodontic treatments by properly adjusting the magnitude and direction of the orthodontic force. However, in most FE analyses, it is not straightforward to import the force-displacement relationship into the FE package. For this reason, the development of other alternative models that depict the stress-strain relationship remains essential for further biomechanical studies of the PDL.
This study used a hyperelastic material model to simulate the mechanical behavior of the PDL in an FE analysis. The absolute errors of the displacement results between the FE analysis and experiment were less than approximately 0.03 mm (Table 1). Although the relative errors in the 5 and 10 N results seem remarkably large, this is due to the relatively small displacement results of the experiment. However, the coefficients of the hyperelastic material used in this study were inconsistent with those used in previous studies (Chang et al., 2014; Natali et al., 2004). One reason for this is that this study used a complete premolar instead of a sliced sample to determine the holistic biomechanical behavior. Furthermore, a larger sample size (n = 5) was applied in this research to include biological deviations as well. Despite the time effect (i.e., viscoelastic), our study showed that the PDL could be modeled as hyperelastic material, and the results from the model were in good agreement with the experimental results. From Fig. 5, we can see that the hyperelastic FE model provided a good fit when the applied force was less than 20 N. In orthodontic treatments, the force generated by the coil or spring could reach 200 grams (i.e., about 2 N) but will not exceed 500 grams (Fraunhofer et al., 1993). For this reason, the hyperelastic model is applicable for clinical applications. The approximate hyperelastic model could also increase the confidence in the FE analysis by facilitating proper predictions of the stress/strain level and distribution, which could help in understanding the mechanobiology of the PDL.

### Table 1  Displacement (mm) difference between the FE analysis and experiment.

<table>
<thead>
<tr>
<th>N</th>
<th>5 N</th>
<th>10 N</th>
<th>20 N</th>
<th>40 N</th>
<th>60 N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td>0.080</td>
<td>0.140</td>
<td>0.227</td>
<td>0.384</td>
<td>0.472</td>
</tr>
<tr>
<td><strong>FE analysis</strong> (hyperelastic)</td>
<td>0.111</td>
<td>0.171</td>
<td>0.252</td>
<td>0.351</td>
<td>0.417</td>
</tr>
<tr>
<td><strong>Absolute error (mm)</strong></td>
<td>0.031</td>
<td>0.031</td>
<td>0.025</td>
<td>0.033</td>
<td>0.055</td>
</tr>
<tr>
<td><strong>Relative error (%)</strong></td>
<td>38.75%</td>
<td>22.14%</td>
<td>11.01%</td>
<td>8.59%</td>
<td>11.65%</td>
</tr>
</tbody>
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Fig. 5 The force-displacement relationship predicted from hyperelastic FE model compared to the experimental results.
The biological and mechanical function of the PDL are known for not only modulating the surrounding alveolar bone absorption and osteogenesis, but also for dispersing occlusal or accidental impacts. In addition, the PDL plays an important role in bone remodeling, which is the major technique used in orthodontic treatment for controlling tooth movement. Although the empirical model and FE analysis showed good results compared to those of the experiments, some limitations remain to be mentioned. Most researchers have adopted animal models when exploring the PDL; however, the biomechanical characteristics of animals are different from those of natural human teeth. Nevertheless, the protocols established to investigate biological tissue from animals could be translated into human research. However, because biological deviations cannot be avoided in every aspect of biomechanical research, the sample size of the experiment should be as large as possible to eliminate the effects of variation. This study only tested the PDL in tension because this mode is not affected by the geometry of the root. However, the compressive behavior of the PDL still needs further investigation. In addition, the detailed tooth structure, which includes the enamel and dentine, was not modeled in our analyses. Since the Young’s modulus of these two structures was obviously greater than that of the PDL, the effects on the FE results could be ignored. Moreover, the strain rate of the PDL used in this study was not tested because of the quasi-static experimental setup; however, it is possible that higher strain rates will affect the behavior of the PDL.

In this study, we found that decreasing $C_{10}$, $C_{01}$, and $C_{11}$ and increasing $d$ in the FE analysis caused greater axial displacement in tension. Therefore, we adjusted these parameters based on the results of our previous study (Chang et al., 2014) to fit the force-displacement results, which were collected from the experimental samples. Since the current study is not an optimization analysis, there are no cost or objective functions to be minimized and it is acceptable to have another set of these parameters. Further study is necessary to determine the complete biomechanical behavior of the human PDL, such as investigations with more samples or in different oral regions.

5. Conclusion

In vitro study of the periodontal ligament was performed and the results revealed that the power function could be used to describe the force-displacement relationship of the PDL. Furthermore, by using the hyperelastic characteristics as the constitutive equation, the biomechanical behaviors of the PDL subjected to tension less and equal to 20 N could be predicted by the finite element model constructed using micro-CT.

References


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