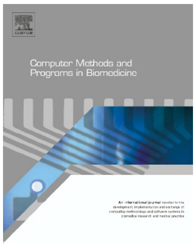
COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE 113 (2014) 749–756

journal homepage: www.intl.elsevierhealth.com/journals/cmpb



Experiment and hydro-mechanical coupling simulation study on the human periodontal ligament

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ARTICLE INFO

Article history:
Received 26 March 2013
Received in revised form
26 November 2013
Accepted 18 December 2013

Keywords:
Periodontal ligament
Biomechanics
Hydro-mechanical coupling
Experiment
Simulation

ABSTRACT

In this paper, a new method involving an experiment in vivo and hydro-mechanical coupling simulations was proposed to investigate the biomechanical property of human periodontal ligament (PDL). Teeth were loaded and their displacements were measured in vivo. The finite element model of the experiment was built and hydro-mechanical coupling simulations were conducted to test some PDL's constitutive models. In the simulations, the linear elastic model, the hyperfoam model, and the Ogden model were assumed for the solid phase of the PDL coupled with a model of the fluid phase of the PDL. The displacements of the teeth derived from the simulations were compared with the experimental data to validate these constitutive models. The study shows that a proposed constitutive model of the PDL can be reliably tested by this method. Furthermore, the influence of species, areas, and the fluid volume ratio on PDL's mechanical property should be considered in the modeling and simulation of the mechanical property of the PDL.

1. Introduction

The physiological mechanism primarily responsible for tooth movement in response to force is the periodontal ligament (PDL) [1]. However, the material model of PDL is far from perfect [2]. A lot of elastic models, such as linear elastic model [3,4], bilinear elastic model [5], and hyperelastic model [6,7] have been proposed, whereas these models can only describe the PDL's instantaneous property but not its viscous property. A linear viscoelastic model [8] and a hyper-viscoelastic-damage model [9] have been developed. Viscoelastic model is a type of phenomenological model which describes the PDL's property as a whole. Under an applied load, there is a complex interaction between the PDL's solid phase and fluid phase, which cannot be well described with these proposed viscoelastic models [14]. Some models based on PDL' inner structure have been developed. In one model, the crimped fibers is reduced to straight ones and homogenized to a fiber reinforced material [10]. In another model, both the fibers and the matrix are regards as viscoelastic materials and combined into a single model [11]. Recently, hydro-mechanical coupling method has been used to model the mechanical property of PDL. In hydro-mechanical coupling models, matrix of PDL is described as fluid; while the solid phase in the PDL has been described with the linear elastic model [12], the hyperfoam model [13], and so on. There is still not a recognized model.

For the difficulties in doing human experiment in vivo, proposed PDL's material models have not been fully validated [2]. Some animal experiments [15,16] have been conducted, but

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http://dx.doi.org/10.1016/j.cmpb.2013.12.011

Fig. 1 – Dental plaster model impressed before the experiment.

there is still a lack of proofs to verify the consistency between animal PDL and human PDL. There were a few experiments [17–19] on the human PDL in vivo, in which the tooth displacement under load was measured with devices outside of the mouth. In these experiments, the force truly acted on the tooth may vary with the head movement. Also, the measured tooth's displacements may be neither the total displacement nor an easily determined component, for it is hard to assure the conformity of the measuring direction to the tooth's deflection direction. Furthermore, although there are some reports on building a fine dental model [20,21], the loads in experiments are difficult to be accurately simulated to reliably test a proposed constitutive model of the PDL. As a result, a new method involving experiments in vivo and hydro-mechanical coupling simulations is proposed in this study to investigate the biomechanical property of human PDL.

2. Materials and methods

2.1. *Experimental methods*

A 19-year-old male volunteer, whose second premolars were to be extracted in the treatment, was recruited to conduct this test. One week after the teeth extraction, the experiment was done during a return visit. Before the test, the volunteer's dental tissue was scanned with CT (Hispeed NX/I, GE, America) to build a digital model. After brackets were attached to the teeth, the dental arch was impressed with silica gel and a dental cast model was made (Fig. 1). The dental cast model was then scanned with a laser scanning machine (EXAscan, Creaform, Canada). With the derived data, a surface model of the brackets and the dental arch was built. Thereafter, the volunteer's first premolar and the first molar were loaded with rubber stripes of different lengths in turn (Fig. 2). The lengths were estimated according to the expected magnitude of force and the measuring distance between the volunteer's first premolar and first molar. The rubber stripes were attached to the top jack catch of a micrometer calipers (110-011, Anyi, China) with a resolution of 1 μm. The bottom jack catch of the micrometer calipers was laid on the brackets attached to the measuring teeth to load the teeth and measure the distance at the same time (Fig. 3). The distance was also measured before load to calculate the relative displacement of the two teeth under load. A load was applied for three times in an interval of 5 min. Four loads were applied in a same interval of 5 min. After the experiment, the magnitude of the load force generated by rubber stripes was calibrated by making the readings of the calipers to the same as that in the experiment on a test machine with a resolution of 0.05 N (NK-10, Aidebao, China) (Fig. 4). The measured data of the same load were averaged to be used in this study.

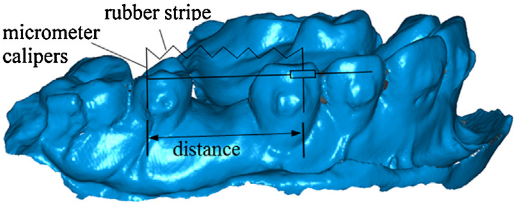

Fig. 2 – Digital model derived from laser scanning of the dental plaster model.

2.2. *Finite element analyses*

2.2.1. *Mesh and boundary conditions*

A three-dimensional dental model of the separated teeth, the PDL, the alveolar bone, except for the brackets (Figs. 5 and 6), was built based on the CT scanned data. A uniform thickness of 0.2 mm was assumed for the PDL. In the subsequent finite element simulation, both the teeth and the alveolar bone were modeled as rigid surfaces. The reference points of the teeth were made to locate on the brackets where the teeth distance was measured. To determine the reference points' location in the model, the surface model including brackets and teeth derived with laser scanning (Fig. 2) was registered to the three-dimensional dental model by matching the teeth's surface. The reference points of the two teeth were linked with a cable model, on which a bolt load was applied to simulate the experimental load on teeth. The interaction between the alveolar bone and the PDL was modeled as bond contact, so

Fig. 3 – Scene of experiment. Rubber stripes were attached to the jack catch at one end while the other end of the jack catch was laid on the brackets to load teeth and measure the distance simultaneously.