Validation of a 3-D simulation model for orthodontic tooth movement

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Orthodontic tooth movement depends on the induction of bone resorption and bone deposition around the tooth by mechanical forces. In some cases the tooth moves very fast while in others it may move only very slow. In addition, tooth movement sometimes induces extensive root resorption. The origin of these differences may lie in the mechanical conditions in the tissues around the tooth. Many studies on the effects of mechanical forces on tooth movement, and on the tissues around the tooth are conducted in animals such as rats and dogs. The aim of this project was to validate a 3-D simulation model for orthodontic tooth movement based on experiments in dogs. Such a computer model may greatly reduce the use of animal models for orthodontic research. In the present project we improved this model, and validated it with an in vivo experiment in beagle dogs.

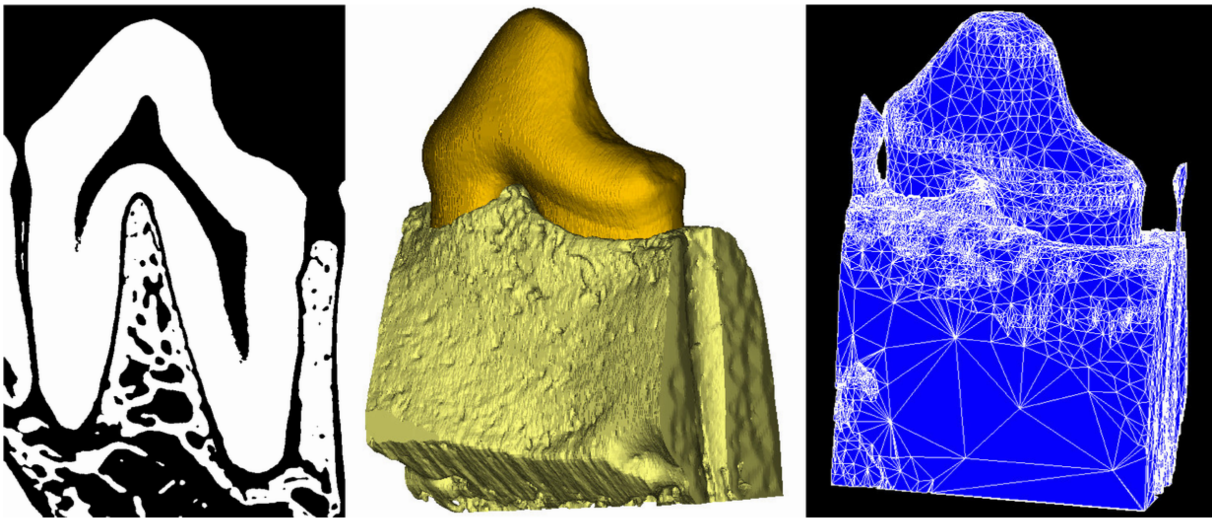

Figure1: Finite-element modeling of a dog tooth.
The representations in 1a and 1b are derived from a micro-CT scan of a dog premolar. A vertical section of the 3-D scan can be made with appropriate software (1a). The surface contours of the bone (greenish) and the tooth (yellow) can be represented in 3-D (1b). In 1c the tissues are divided into 4-node elements to compose the finite-element model.

Finite-element modeling

Several years ago we already constructed a model of a dog premolar based on histological sections of the tooth and its surrounding structures. Recently, it became possible to construct a 3-D model of a tooth based on micro-CT scanning. This leads to a much higher accuracy of the model (Fig. 1a,b). The computer simulation model for tooth movement consists of a 3-D model of a tooth divided into small elements (Fig. 1c). Each element in the model is assigned certain mechanical properties like stiffness and elasticity. These properties should resemble the actual in vivo properties of the tissues as much as possible. The resulting computer model is called a finite-element (FE) model. Such a model can calculate changes in the stresses and strains (deformations) in the tissues after the application of a force. The highest deformations occur in the ligament around the root of the tooth, the periodontal ligament (PDL). The PDL is a thin layer of soft connective tissue that attaches the tooth to the jaw bone. We think that deformations in this tissue initiate the biological reactions leading to tooth movement. In collaboration with the Technical University Eindhoven we improved the properties of the PDL in the model by including the collagen fibers that attach the tooth to the jaw bone (Fig. 2). The PDL then behaves like a fiber-reinforced material. The chosen orientation of the collagen fibers depends on the location within the PDL and is derived from histological samples.

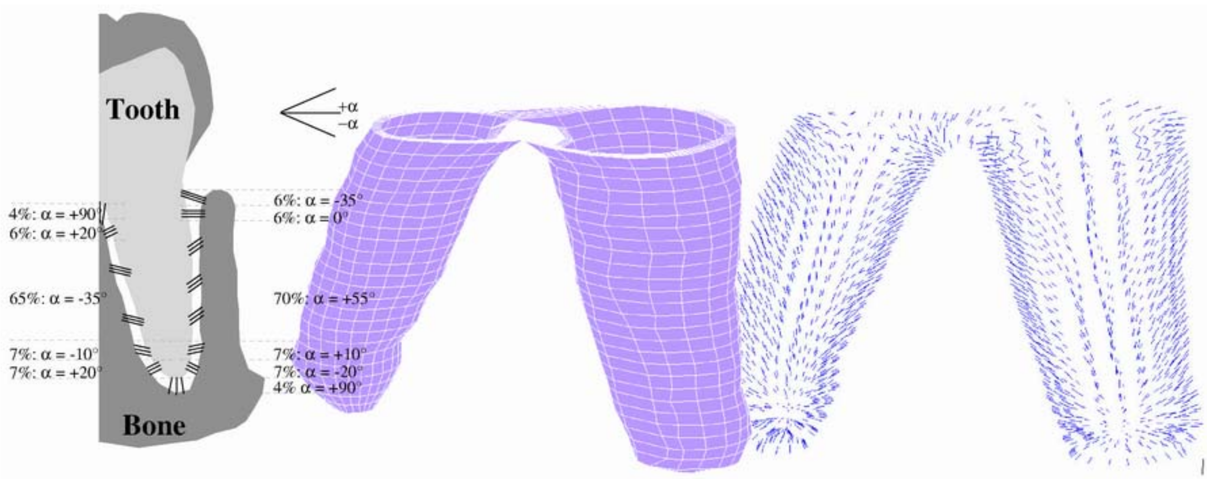

Figure 2: Modeling of fibers in the PDL.
The orientation of the collagen fibers attaching the tooth to the bone varies in different areas of the PDL (2a). The PDL can be isolated from the model (1b) and fibers in the right orientation can be added (1c).

Validation experiments

The final aim was to obtain data on the biomechanical properties of the PDL in a living dog to validate the simulation model. Orthodontic appliances were constructed to apply accurate forces to the teeth. The forces used were 50, 100 and 300 cN. Each appliance was equipped with an electromagnetic sensor to measure tooth movement during 5 hours. The data were used to construct time-displacement curves (Fig. 3).

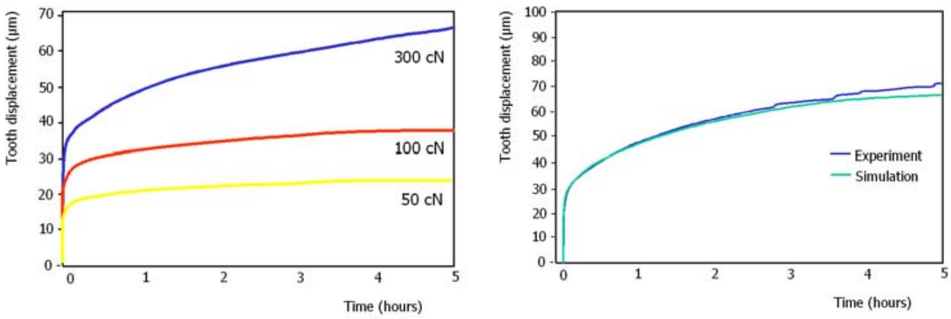

Figure 3: Validation experiments.
The experimental time-displacement curves for 50 (green), 100 (blue), and 300 (red) cN are shown to the left. At the right, a simulated displacement curve is shown in comparison with the experimental displacement at 300 cN. The experimental displacement curve and the simulated curve are nearly identical.

The experimental curves (Fig. 3, left) show that displacement of the teeth occurs in two phases, a short rapid phase and an extended slow phase. The tissue response is similar at all three force levels. The maximum displacement increases with the force. The right panel in Figure 3 shows that the simulated displacement in a time frame of 5 hours is similar to the experimental displacement with a force of 300 cN. We achieved this by modeling two phases in the displacement process. The first phase represents a rapid redistribution of tissue fluid within the PDL. The second phase represents a slow deformation (creep) of the solid matrix of the PDL. This type of reaction is characteristic for soft connective tissues and is called biphasic behavior. The results show that our simulation model can mimic the in vivo displacement by representing the PDL as a fiber-reinforced biphasic material. In further research, the model will be extended to the later phases of tooth movement.

Reference

Van Driel WD, van Leeuwen EJ, Von den Hoff JW, Maltha JC, Kuijpers-Jagtman AM. Time-dependent mechanical behavior of the periodontal ligament. Proc Inst Mech Eng 214: 497-504, 2000.