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Technical note

Analytical determination of stress patterns in the periodontal ligament during orthodontic tooth movement

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ABSTRACT

A dedicated software package that allows simulation of tooth movement can lead to shortening of the treatment program in orthodontics. A first step in the development of this software is the modelling of the movement of a single tooth. Forces applied to the crown of the tooth are transmitted to the alveolar bone through the periodontal ligament, stretching, and compressing the ligament, eventually resulting in tooth movement. This paper presents an analytical model that predicts stresses and strains inside this ligament by approximating the shape of the root as an elliptic paraboloid. The model input consists of 2 material parameters and 4 geometrical parameters. To assess the accuracy of the model a finite element model (FEM) was constructed to compare the results and the influence of the eccentricity of the root was studied. The results show that the model is able to successfully describe the global behavior of the PDL and, except at a region near the alveolar crest, the differences between analytical and FEM results are small. In contrast to FEM, the analytical model does not require setting up a 3D-model and creating a mesh, allowing for significantly lower computational times and reducing cost when implementing in clinical practice.

1. Introduction

The primary aim of orthodontics is the prevention, and correction of malocclusion. Currently the choice of the treatment program is based on the experience of the orthodontist and on a trial-and-error procedure. This can lengthen the duration, and thus the cost, of the treatment. A dedicated software package that allows simulation of orthodontic and orthognatic treatments for each individual patient can lead to shortening of the treatment program. A first step in the development of this software is the modelling of the orthodontic movement of a single tooth.

Teeth are surrounded by the periodontal ligament (PDL), a thin membrane consisting of collagen fibers. This ligament provides the attachment of the tooth to the surrounding alveolar bone, and under normal circumstances there is no direct contact between the root and the bone. Forces applied to the crown of the tooth are transmitted to the alveolar bone through this layer, stretching, and compressing the ligament. The resulting biological response in the periodontal ligament causes the orthodontic repositioning of the tooth [1–3]. Although the exact biological process leading to permanent tooth movement is not yet clear, it is understood that different cell types, like fibroblasts, osteocytes and osteoblast, respond to the changes in mechanical environment. Whether the cells can sense the stretching of the surrounding matrix, or respond to the fluid flow inside the ligament, to determine their response, it is important to know the strains and stresses surrounding the root in order to predict tooth movement.

Provatidis [4] presented an analytical way of predicting significant quantities (stresses, strains, strain-energy breakdown, tooth mobility and the position of the centre of resistance) relating to the horizontal translation of a single-rooted tooth. Provatidis followed Haack and Haft [5] in representing the root of a maxillary central incisor as a paraboloid, surrounded by the ligament. However, the shape of the root can be approximated better by using an elliptical paraboloid [6]. Furthermore, in orthodontic tooth movement, not only pure translation is important. This paper presents a model that uses the same approach followed by Provatidis, to predict not only horizontal translation, but also random tooth movement approximating the shape of the root as an elliptic paraboloid. To assess the accuracy of the model a finite element model (FEM) was constructed to compare the results. Finally the influence of the eccentricity of the root was studied.

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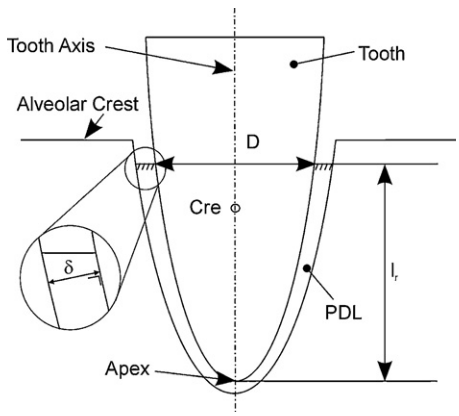

Fig. 1. Tooth geometry and basic definitions: the tooth is surrounded by the periodontal ligament (PDL), which has a thickness δ, measured perpendicular to the root surface. The tooth axis is vertical, and the alveolar crest is assumed to be horizontal. The length l_r of the tooth is defined as the distance along the tooth axis from the apex to the top of the PDL. The diameter D is measured at the alveolar crest. Applying a horizontal force to the center of resistance (Cre), located on the tooth axis, will result in a pure translation in the direction of the force.

2. Materials and methods

2.1. Previous models

The starting point of this article is a model of Provatidis [4], who presented an analytical way of predicting stresses and strains inside the PDL during horizontal translation of the tooth. The tooth root was approximated using a paraboloid, as was done by Haack and Haft [5]. By using the analytical formula for a paraboloid, Provatidis calculated the displacement of each point of the root resulting from a horizontal translation of the root. Using these displacements, he approximated the strains inside the ligament, and assuming the PDL is linear and isotropic, stresses are calculated.

The model explained in this article uses the same approach, but improves the model of Provatidis in three ways. Firstly, not only horizontal translation of the root is included, but also the model is expanded to predict stresses and strains resulting from all types of movement of the root, both translation in any directions and rotation around any axis. Secondly, since the shape of the root can be approximated better by using an elliptic paraboloid [6], the root is modelled as such, and not as an axisymmetric paraboloid.

2.2. Assumptions

A maxillary central incisor was chosen as a typical case of a single-rooted tooth and the following nominal geometrical data were used [4,7]: root length $l_o = 13.0$ mm and root diameter $D_o = 7.8$ mm. The tooth axis is vertical, and the alveolar crest is assumed to be horizontal (Fig. 1). The periodontal ligament is assumed to have a thickness $\delta = 0.229$ mm [4,8,9], measured perpendicular to the surface of the root. The eccentricity e of the root, as defined in the next section, determines the ratio between the short and the long axis of the ellipse and lies between 0 and 1. A circle has an eccentricity $e = 0$, while a line has $e = 1$. For this study, the eccentricity of the tooth root was varied between 0 and 0.6.

After force application to the tooth, equilibrium in the periodontal ligament is reached in several minutes, while bone remodeling occurs on a much larger time scale. Therefore, bone remodeling does not influence initial displacements on the short time scales investigated in this study. Furthermore, the forces applied in orthodontic treatment are small and the alveolar bone and the root have a Young's modulus which is much higher than that of the PDL. For these reasons it is a good approximation to model the alveolar bone and the tooth root as rigid bodies.

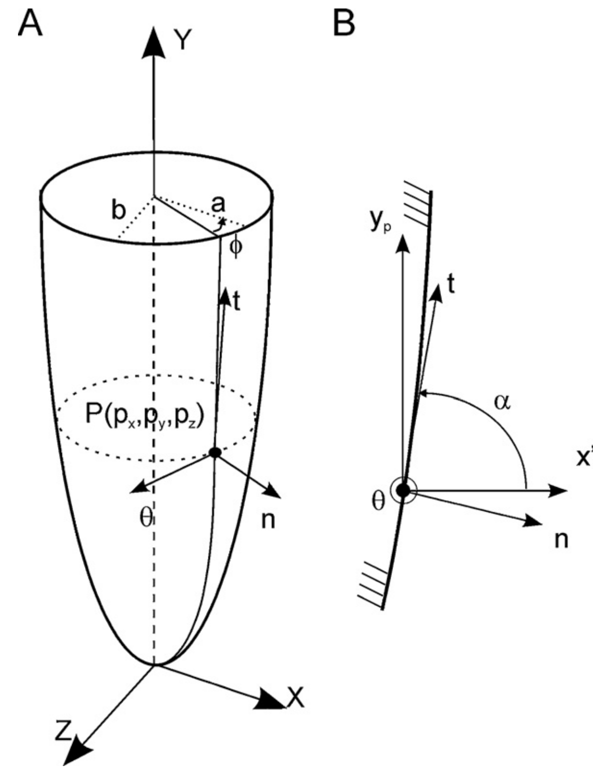

Fig. 2. Three different coordinate systems are defined on the root. (A) The global coordinate system (x, y, z) has its origin in the apex of the root and the Y-axis coincides with the vertical tooth axis. In every point P (p_x, p_y, p_z), a local coordinate system (n, t, θ) is defined. The n-axis is normal to the surface, while the θ-axis is tangential to the surface and horizontal. (B) A second local coordinate system (x', y_p, θ) is defined in every point P, to aid the transition between (x, y, z) and (n, t, θ).

The type of tooth movement that occurs in response to an applied force is determined by the location of the centre of rotation relative to the centre of resistance. The centre of resistance is defined as the point on the tooth axis where application of a horizontal force results in pure translation of the tooth in the direction of the force. It is thus determined by the geometrical properties of the root and the material properties of the PDL. Although the periodontal ligament (PDL) is a non-linear and anisotropic material with a time-dependent hysteresis behavior, the location of the centre of resistance and the centre of rotation can be approximated within the margins of clinical results by assuming the periodontal ligament is a linear, isotropic material [10]. The Young's modulus used for the PDL is $E = 0.68$ MPa and the Poisson coefficient is $\nu = 0.49$ [4]. With these material properties, and the dimension of the root as described above, the centre of resistance is located at 8.43 mm from the root apex.

2.3. Geometry

A global three-dimensional coordinate system (x, y, z) is attached to the tooth. As shown in Fig. 2 the origin lies at the tooth apex, the lowest point of the root and the y-axis coincides with the vertical tooth axis while the XZ-plane is a horizontal plane parallel to the alveolar crest. In addition, a local coordinate system (n, t, θ) is defined for every point $P(p_x, p_y, p_z)$ of the root (Fig. 2). The n-axis is normal to the tooth surface, the θ-axis is horizontal and perpendicular to the unit vector $\vec{n}$ along the n-axis, the t-axis completes the right-handed, orthogonal coordinate system. To facilitate transformation between the global and the local coordinate system, a local