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Finite Element Method Analysis of the Tooth Movement Induced by Orthodontic Forces

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ABSTRACT

The finite element method is a useful technique for measuring structural stress and for movement analyses. The objective of this investigation was to get a more accurate estimation of tooth movement depending on application point when a tipping orthodontic force is applied. The tree-dimensional model of un upper canine, consisting of 4,000 hexahedron elements with 2,367 nodes was obtained. Horizontal, orally directed 1N tipping orthodontic force was applied to the model on five different levels of the tooth crown. The three–dimensional mathematical finite element model is useful in analyzing the tooth movement in response to orthodontic forces. The tipping tooth movement is greater if the force is appled closer to its neck, or more gingivally.

Key words: *finite element method, orthodontic forces, tooth movement*

Orthodontic treatment is based on the use of various appliances which produce a force that causes orthodontic tooth movement[1]. Orthodontic appliance activation produces force system which is transferred on teeth and supporting structures. The final result is tooth movement. Orthodontic forces in contact with teeth and the supporting structures are immediately transformed. Tissue reactions induced by orthodontic loads depend on their anatomical, physiological and mechanical characteristics and are also characterized by growth and remodeling processes[2,3]. Initial tissue reaction is mechanical and depends quantitatively and qualitatively on tissue characteristics. The mechanical reaction is followed by biological[4]. Therefore, it is very important to know the basic principles of the orthodontic force acting so the controlled tooth movement is reached[5,6]. Force magnitude and direction are important factors in evaluating the orthodontic appliances and tissue reaction[7,8] and it greatly influences the treatment success. The forces delivered

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from an orthodontic appliance can be determined by direct measurement by means of suitable instruments or, in part, by mathematical calculation[9]. It should be remembered that most orthodontic appliances deliver a relatively complicated set of forces and moments. In clinical studies, therefore, it is useful to employ appliances of simple construction in which forces are more easily and accurately determined. For the same reason a clinical study in which force variables are controlled is likely to supply more information than are data taken from patients in routine orthodontic practice[10]. The finite element method (FEM), which was introduced as one of the numerical analyses[11,12] has become a useful technique for stress analysis in biological systems [13–18].

The problem of tooth stresses is very complicated because of the non-homogeneous character of tooth material and the irregularity of tooth contours. The tooth structure consists ofpulp, cementum, periodontal ligament, and bone. Each of these has widely varying properties. The problem is further complicated by large variations (both in magnitude and direction) of chewing forces[19]. The objective of this investigation was to obtain a more accurate estimation of tooth movement depending on application point when a tipping orthodontic force is applied.

Materials and Methods

An upper canine, extracted for a periodontal reason, served as the pattern for construction of a mathematical model. After the tooth had been well cleaned it was placed in transparent acrylic. Layers 0.5 mm thick were ground off, vertically on the longitudinal axis of the tooth by a paralelometar (Combilabor CL-MF, Hereaus – Hanau). Each section was recorded by a video camera, Sony CCD TRV 825 E Hi 8mm. Sixty photographs of the tooth sections were taken. The camera was connected to a computer (PC Pentium II 64 Mb RAM, 350 MHz, 8.4Gb HDD) via a S-VHS cable, and a frame grabber – video adapter was used for digitalisation of the photographs (Ima Scan, resolution 1,024–768 in PAL format with 625 horizontal lines and 16 Mb video memory). In this way 60 cross-sections of the tooth were defined.

The contours of the cross-sections of he tooth were read into the CAD programme AutoCAD Mechanical Desktop 2.0, where the three-dimensional geometry was defined from the curve of the cross-section of the tooth by »lofting« method. The drawings were converted into standard IGES format, which ensured their readability in different CAD applications, including the NISA programme, in which the calculation was performed by the FEM. Thus a three-dimensional mathematical model of the upper canine was obtained, on which periodontal ligament was modelled for the length of the whole root, 0.25 mm in width. After that the supportive bone was modelled. The cortical bone was modelled 2 mm thick, with underlying cancellous bone.

The material properties of tooth, PDL, both cortical and cancellous bone used in this study have been experimentally determined. The material properties used were the average values reported in literature[20] (Table 1). Three-dimensional hexahedron elements were used for modelling, with six nodes and three grades of freedom per node.

TABLE 1
MECHANICAL PROPERTIES OF THE TOOTH, PDL AND ALVEOLAR BONE

	Young`s Modulus ($Nm^{-2)}$)	Poisson`s ratio
Cancellous bone	0.5×10^9	0.3
Cortical bone	13.7×10^9	0.3
PDL	5×10^6	0.45
Tooth	19.6×10^9	0.3

The whole model comprised 4,000 elements in the form of a hexahedron, and 2,367 nodes, amounting to a total of 7,101 grades of freedom (Figure 1). Horizontal, orally directed 1N tipping orthodontic force was applied to the model on five different levels of the tooth crown. Tooth movements were observed and calculated for each applied load. The results of the calculation are shown in figures, registered in GIF format.

Results and Discussion

In this investigation simple horizontal orally directed force, strength 1N was applied on five different levels of the tooth crown, perpendicular to its longitudinal axis. The result of such force application is simple tipping of the tooth. During such movement the angle of the longitudinal axis of the tooth changes. The most frequent clinical situation, in which such an effect of force and tooth movement occurs, is the retrusion of the frontal teeth by labial bow of the activator or active plate.

Maximal tooth movement of 4.39×10^{-4} mm (Figure 2) was registrated at the application of force strength 1N at the tooth cusp. By moving the point of force application for 2 mm towards to apex, tooth movement of 6.83×10^{-4} mm (Figure 3) has been noticed. Force strength 1N, which affects the labial surface of the tooth 4 mm under the cusp caused maximal tooth movement of 1.83×10^{-4} mm (Figure 4). In the fourth experiment the force strength 1N was applied in a horizontal direction 6 mm from the tooth cusp apical. The result was maximal tooth movement of 1.07×10^{-4} mm (Figure 5). After the application of the force on the labial surface on the neck of the tooth maximal tooth movement of 7.86×10^{-5} mm (Figure 6) was measured. Based on calculated tooth movement of our study

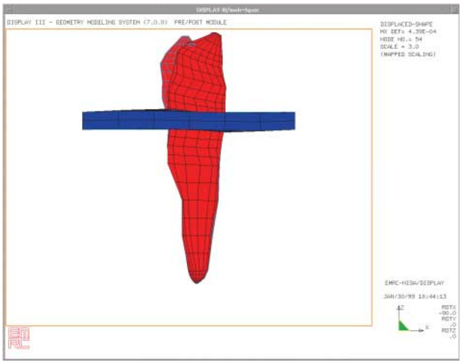

Fig. 2. Application of 1N tipping force under the tooth cusp.

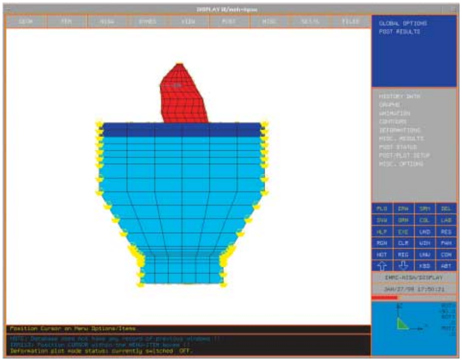

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Fig. 1. Three-dimensional finite element model of the upper canine. The model comprises the tooth, PDL, and alveolar bone.

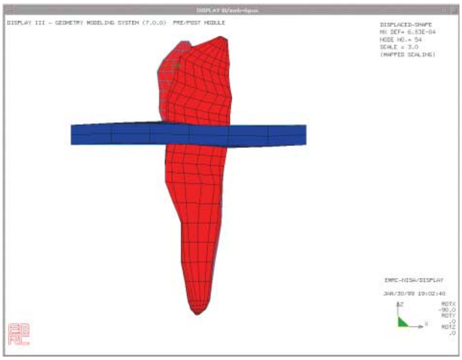

Fig. 3. Application of 1N tipping force on the labial surface 2 mm under the tooth cusp.

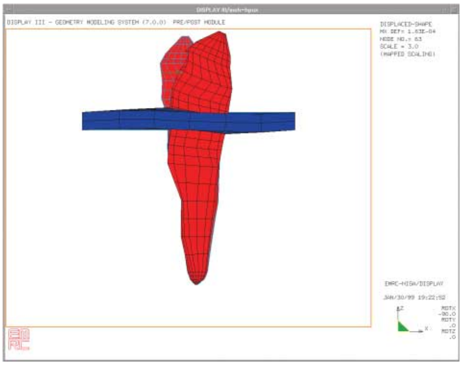

Fig. 4. Application of 1N tipping force on the labial surface 4 mm under the tooth cusp.

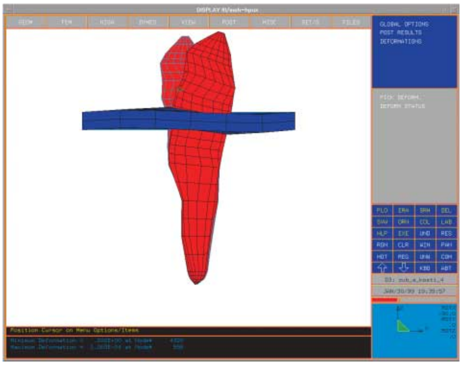

Fig. 5. Application of 1N tipping force on the labial surface 6 mm under the tooth cusp.

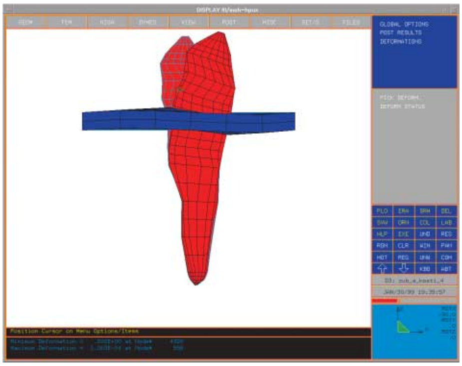

Fig. 6. Application of 1N tipping force on the labial surface close to the tooth neck.

several conclusions can be drawn. It is obvious that the tooth movement is greater if the force is applied closer to its neck, or more gingival. An exception is the result of first and second experiment. In the first experiment a smaller tooth movement was registered than in the second although the force was applied more apically. That can be explained by fact when the force is applied on its cusp, on a small surface, and cannot cause tooth movement because of great deformation. It is also important to point out that in the present investigation the duration of the effect of force was neglected, and therefore the results can only be applied to the initial phase of the exertion of the force on the tooth and tooth movement. It should be emphasized that the finite element method does not give completely accurate results and on the whole does not represent a true condition, but rather is another more attempt at approach in this problem.

Conclusions

Based on the result of this study of tooth movements caused by tipping 1N strength force applied to the mathematical model of the tooth several conclusions can be drawn.

The three–dimensional mathematical finite element model is useful in analyzing the tooth movement in response to orthodontic forces.

The tipping tooth movement is greater if the force is applied closer to its neck, or more gingivally.

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ANALIZA POMAKA ZUBA NASTALIH DJELOVANJEM ORTODONTSKIH SILA NA ZUB METODOM KONAČNIH ELEMENATA

SAŽETAK

Metoda konačnih elemenata pokazala se uspješnom u raščlambi prijenosa sila, naprezanja i pomaka u biološkim sustavima. Svrha ovog istraživanja bila je utvrditi razlike u pomacima zuba ovisno o mjestu aplikacije sile koja uzrokuje njegovo naginjanje. Na temelju ekstrahiranog gornjeg očnjaka izrađen je trodimenzionalni matematički model koji se sastojao o 4000 elemenata oblika heksaedra i 2367 čvorova. Na model je aplicirana horizontalna, oralno usmjerena sila jačine 1N na pet različitih razina krune zuba. Rezultat djelovanja takve ortodontske sile je naginjanje zuba. Metoda konačnih elemenata pokazala se uspješnom u analizi pomaka zuba nastalih djelovanjem ortodontske sile. Pomak zuba je bio veći što je sila bila aplicirana apikalnije, odnosno bliže vratu zuba.

Ključne riječi: metoda konačnih elemenata, ortodontske sile, pomak zuba