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Numerical simulation of tooth mobility using nonlinear model of the periodontal ligament

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1. Introduction

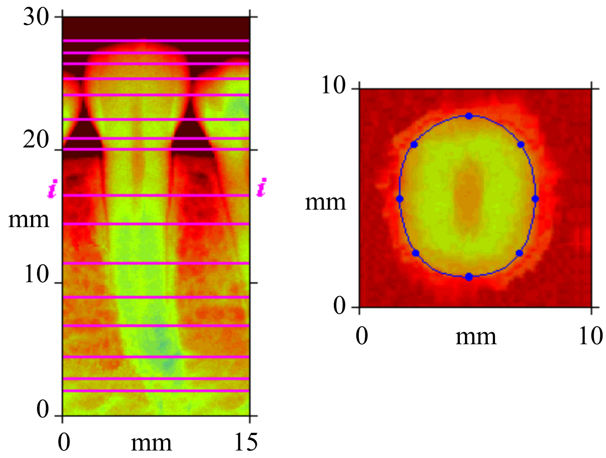
A branch of dentistry which is concerned with studies, prediction and treating of a bite (inclinations of the teeth from the optimal position) is called orthodontics. Anomalies of the bite can cause early loss of teeth, parodontosis, and diseases of periodontal ligament and joint of the lower jaw. Anomalous bite is corrected applying methods of orthodontic treatment. The main point of such treatment is to change position of a tooth or a group of teeth in the dental arch [1]. With this aim in view, a special appliance – an arch wire bent in curves or loops is attached to the bracket on your teeth. Adjusted orthodontic wire creates a mechanical impact. A system of forces created by the orthodontic appliances causes remodeling of the dental tissue. It means that in places affected by periodontal ligament, the compressed bone is resolving (disappearing) and new structures of bone tissue are formed in the extension places. Thus the tooth changes its place. In order to control a tooth movement it is necessary to establish a ratio of the torque and force in the orthodontic appliance – bracket, a position of the tooth resistance and rotation centers.

Research object is to establish the main biomechanical characteristics of the canine – the centers of rotation and resistance, to present recommendations for the tooth movement control during orthodontic correction.

2. Finite element model of the tooth

A human tooth is a body of irregular geometric form and it is not so easy to form its precise spatial model. A lower jaw canine was chosen for research and in order to describe its geometry the photos received by means of computer tomographer were used. Images of any dental layer (section) are presented in these photos [2].

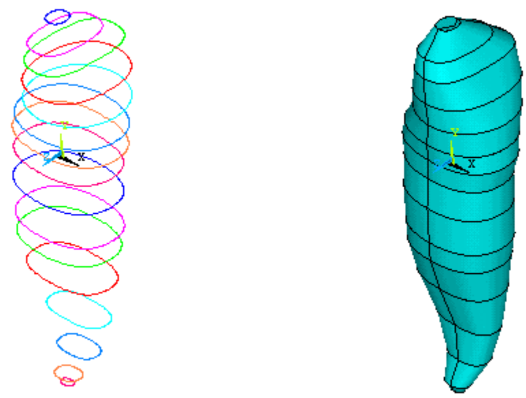
Images presented in tomographic photos were received by means of intersecting a tooth with projecting planes: first of all through the longitudinal axis of a tooth Oy (a vertical one) (Fig. 1, a) and later – alongside planes perpendicular to this axis (16 planes) (Fig. 1, b). Contours of a tooth intersections received by means of a tomographer were processed applying software of the mathematical modeling – MATLAB. The software created for this aim can read tomographer photos and to establish characteristic points of a tooth cross-section contours. Here indeterminacy of measuring of coordinates of characteris-tic points of a tooth section contours equals to ± 0.05 mm. Received coordinates of the points are used for formation of a tooth geometrical model applying the systems finite element method ANSYS.



a b

Fig. 1 Tomographic photos of the canine: a – longitudinal section of the tooth; b – the *i*-th cross-section of the tooth

In order to form geometrical model of a tooth, points of each cross-section are interpolated by means of a closed cubic spline and then curves describing the research object received in different working planes are linked up to the spheres from which spatial volumes are formed later (Fig. 2).



a b

Fig. 2 Geometrical model of the tooth: a – geometry describing curves; b – volumetric model

Models of periodontal ligament and alveolar bone are formed analogously having processed tomographic images.

In order to analyze biomechanics of a tooth-periodontal ligament-alveolar bone system a spatial problem is solved by means of finite element method. A finite element model is formed applying the system ANSYS, disintegrating a volumetric model into finite elements of the SOLID45-type. This element is a square prism in peaks of which are nodes (8 nodes in the element). Each node has 3 degrees of freedom: displacements towards directions of axes X, Y and Z. There are 32760 of interlinked nodes and 32340 elements in the formed model of the tooth-periodontal ligament-alveolar bone finite elements (Fig. 3).

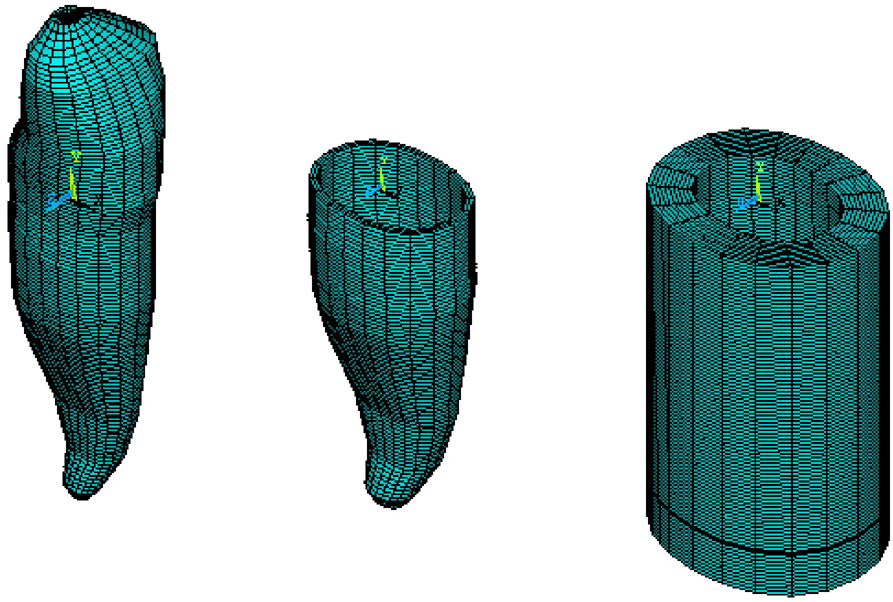


Fig. 3 Finite element model of the tooth-periodontal ligament-alveolar bone system: a – tooth; b – periodontal ligament; c – alveolar bone

A tooth and alveolar bone are modeled as purely of monolithic material in the finite element model, i.e. isotropic and homogenous. Elastic properties of such material [3] are described by means of a Young's modulus E and Poisson's ratio ν (Table 1). According to the literature [3, 4] sources such simplification of the calculation model has no material impact on the problem solution.

Table 1

Material properties

Material	Young's modulus E, Pa	Poisson's ratio ν
Tooth	$2\cdot10^{10}$	0.15
Alveolar bone	$1.4\cdot10^{10}$	0.15

Periodontal ligament, a material between the tooth and alveolar bones, distinguishes itself with its nondirect qualities [5 - 7]. From that how fairly qualities of the periodontal ligament are described it significantly depends if the calculated tooth displacements are close to actual ones. Thus while modeling a system of a tooth-periodontal ligament-alveolar bone it is necessary to form a model describing periodontal ligament properties as precise as possible. Nonlinear properties of the periodontal ligament were described by the nonlinear dependence of tension on strains.

For description of nonlinear properties of periodontal ligament by means of nonlinear dependence of stresses on strains, Toms S.R. at all experimentally received and later approximated dependence of stress-strain is used (Fig. 4) [6 - 8].

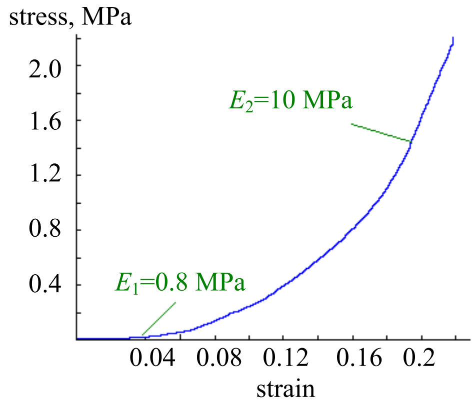


Fig. 4 Periodontal ligament dependency of stresses on strains

Approximately it is possible to separate two sections in this curve with the dependence of stresses on strains close to the linear one: in the first one – Young's modulus of the material E_1 = 0.8 MPa, in the second one E_2 = 10 MPa.

3. Determination of main biomechanical characteristics

Mechanical loads affecting a tooth cause biological changes in the dental tissues that make the tooth to take a new position. Direction and length of the tooth movement depend not only on the force quantity, direction or place of action but also on the place of the tooth centre of resistance and reaction of the dental tissues (periodontal ligament) to the active force.

It is useful to use concepts of the tooth centers of resistance and rotation while discussing the tooth movement [9 - 13]. Centre of resistance of the elastically fixed body (e.g. the tooth root in the bone) is a point of the body acted with some force, which results in tooth tipping towards the direction of the applied force. Centre of rotation is a point around which the tooth rotates under impact of the force. Practically the centre of rotation can be found while choosing an image projection that we are interested in, then drawing a longitudinal axis in initial position and after the tooth displacement and finally finding their intersection point. Unlike the centre of resistance, the position of the centre of rotation is not always within the limits of a tooth and its medium. It can be even rather removed from the tooth. Position of the rotation centre is determined by the tooth impacting loads, their quantity, directions and a place of impact.

The place of the centers of the tooth resistance and rotation is established by solving a small displacement static's problem. A plane of alveolar bone bottom was fixed immovably during the study and loads imitating impact of orthodontic appliances acted in the cheek surface of the crown of the tooth (Fig. 5).

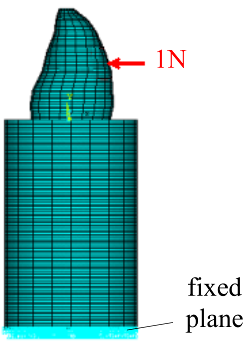


Fig. 5 Boundary condition

Upon applying 1 N force on the cheek part of the crown of the tooth directed towards lingua (Fig. 5), the tooth turns. Having analyzed spectrum of colors describing total displacements of a tooth we found the area of the less tooth displacements (Fig. 6). This is the centre of the tooth rotation. Having changed the force quantity, direction or its action place, the position of the centre of rotation also changes.

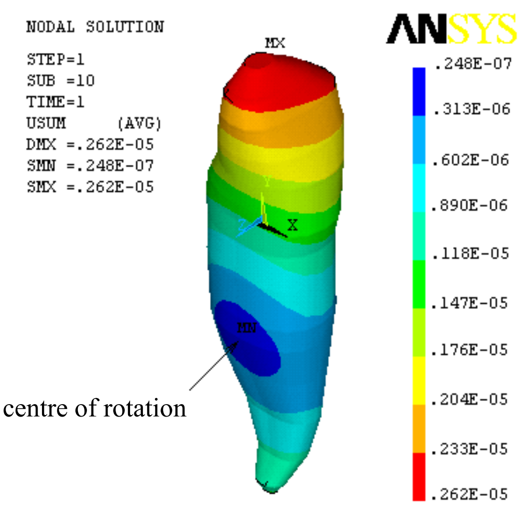


Fig. 6 Tooth displacement

The tooth movement character depends on the force system acting in the centre of resistance. When the tooth is impacted by a couple of forces, it turns around the resistance centre. In this case the tooth resistance centre coincides with the rotation centre (Fig. 7) [9, 10].

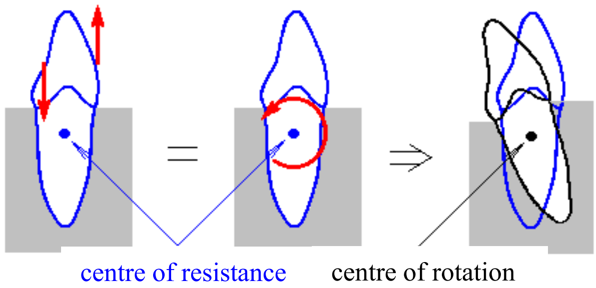


Fig. 7 Tooth centre establishing chart

Position of the canine resistance centre was established on the grounds of this proposition. When the tooth is impacted by a couple of forces (a line of the force impact is parallel to axis Y) (Fig. 8, a), a tooth turns around the axis, shown in Fig. 8, c. In order to establish the place of the centre of resistance in this axis, it is necessary to change the direction of forces acting the tooth. Now the line of the force impact is parallel to the axis Z (Fig. 8, b). Impacted by this couple of forces the tooth turns around the longitudinal axis (Fig. 8, d). The tooth centre of resistance is in the intersection of these two axes (Fig. 8, e).

Having calculated it was received that the tooth centre of resistance is on the longitudinal axis of the tooth. The distance between the centre of resistance and the root vertex is 9.3 mm (59.6 % of the root length), i.e. the centre of the tooth resistance is in the upper third of the tooth root.

Results received by other authors are similar: C.J. Burstone has established that the centre of resistance of the one-root teeth is removed in 58 - 73 % of the root length (canine – in 60 %); R. Nanda has found that the centre of resistance of the upper jaw is significantly higher (about 70 %); D. Vollmer has calculated that a distance between the canine root vertex and the centre of resistance makes 63 % [9, 14 - 18].

4. Tooth movement biomechanics

Direction and length of the tooth movement depends not only on the applied force or direction but also on the spatial position of the force impact line. Translation movement is then, when the force impact line crosses the centre of resistance. When the force impacting line moves away from the centre of resistance, the torque rotating the tooth is created.

However it is uncomfortable and most often impossible in orthodontics to impact the root directly with the necessary force thus in order to control the tooth displacements only the crown of the tooth impacting forces are applied. They are created by special appliances – brackets – an arch wire bent in curves and loops and elastically deformed attached to the teeth.

A desirable tooth movement is received upon impacting the crown of the tooth with a force, which moves it towards desirable direction and a couple of forces that

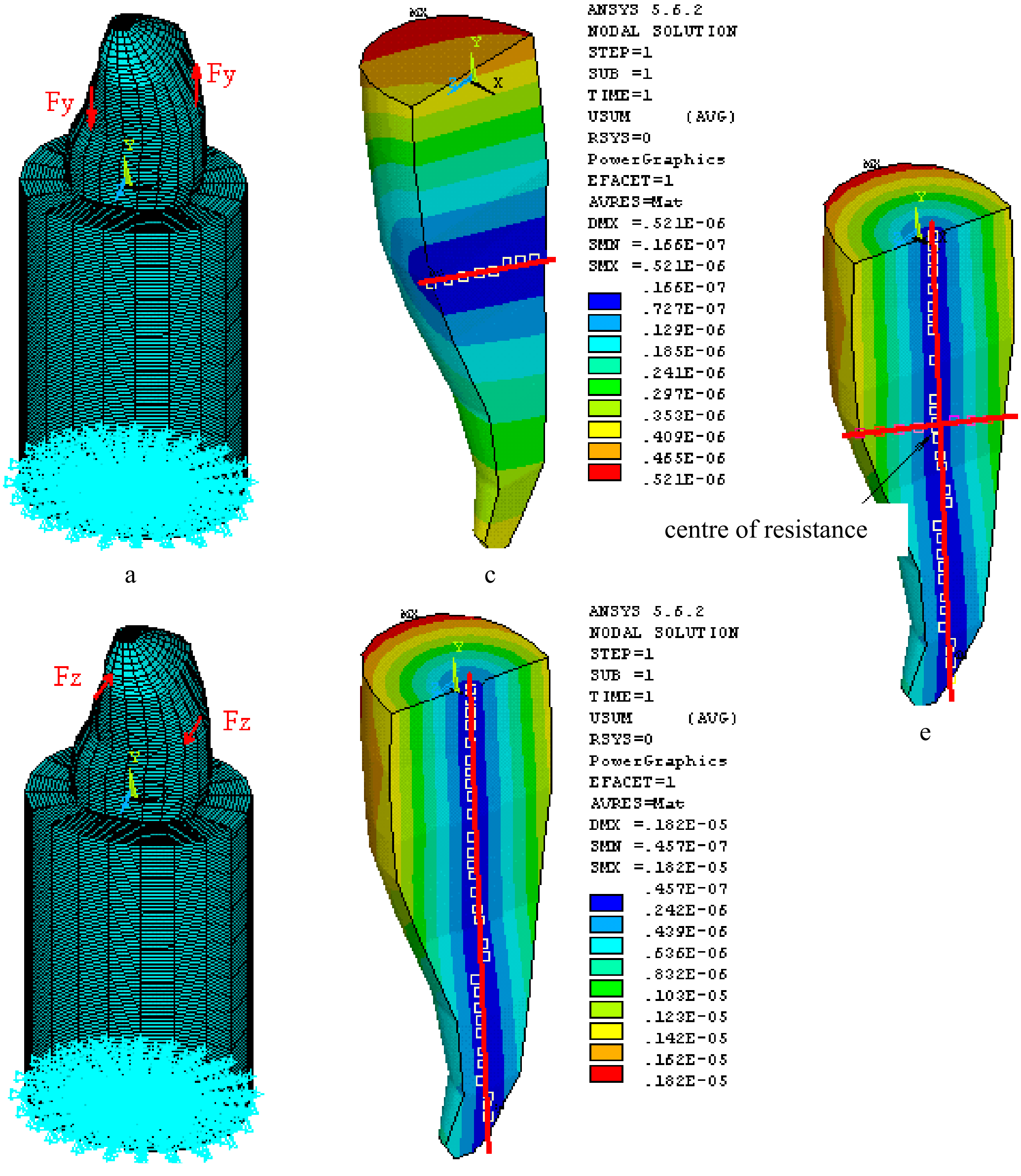


Fig. 8 Establishing of the tooth centre of resistance: a, b – loads acting on the tooth; c, d – rotation axis of the tooth; e – centre of resistance

create a counterbalancing torque. The ratio of this torque and force (M/F) determines the character of the tooth movement (Fig. 9).

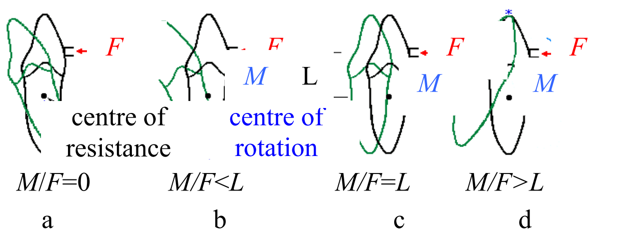


Fig. 9 Types of tooth movement: a – simple tipping; b –controlled tipping; c – translation; d – lingual root movement; *F* – impacting force; *M* – impacting torque; *L* – distance between the bracket and the centre of resistance

When only the force ($M/F = 0$) is acting in the bracket, the tooth turns around the point located in the middle of the root (simple tipping) (Fig. 9, a). When the ratio of the torque and force increases, the centre of rotation is moving away from the centre of resistance towards the root vertex thus creating the so called controlled tipping (Fig. 9, b). If this ratio equals to the distance between the centre of resistance and force impact line, the centre of rotation is infinitely far away from the centre of resistance and the tooth moves as a solid body practically without rotation (Fig. 9, c). When the ratio of the torque and force is bigger than the distance of the centre of resistance and the force impact line, the tooth root vertex displaces more than the crown and such a movement is called lingual root movement (Fig. 9, d) [9, 10].

In order to characterize the movement of the upper jaw canine it was studied how the place of the rotation centre depends on the ratio of the torque and force in the bracket; i.e. the distance between the bracket and the centre of rotation was established.

Different proportions of the torque and the force were received while changing the force value F from 1.85 to 2 N, subject that the torque value was unchangeable and equal to 5.55 N·mm (it was supposed that the torque was positive, when its direction was anti-clockwise).

Dependencies describing the tooth movement character (Fig. 10) were received having approximated calculation results. It can be seen from them that changing the proportion of the torque and force, the position of the centre of rotation is changing according to the exponent law. The formed dependencies allow specifying calculation results of the tooth centre of resistance. In this case, asymptotes show the position of the tooth resistance centre. Thus the centre of resistance of the canine of the upper jaw is removed from the root vertex in 9.4 mm (60.3 % of the root length).

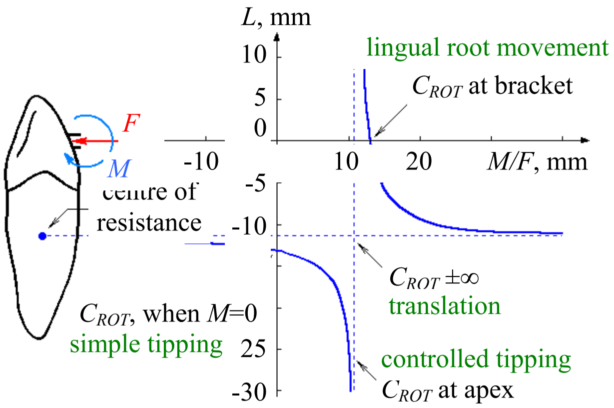


Fig. 10 Dependency of the distance between the centre of rotation (C_{ROT}) and the bracket on the ratio of the torque and force in the bracket

In accordance with the formed dependencies the specified place of the centre of resistance is higher than calculated in a one tenth of a millimeter however the difference makes just about 1 % and can be conditioned by the calculation errors.

Thus by means of these dependencies (Fig. 10) it is possible to establish what ratio of the torque and force should be in the bracket in order to move the teeth in desirable way (Table 2).

Table 2
Impact of the ratio of the torque and force (M/F) on the tooth movement type

Types of movement	Center of rotation	Torque and force ratio (M/F) at bracket, mm
Simple tipping	middle root	0
Controlled tipping	at apex	9.6
Translation	± ∞	11.2
Lingual root movement	at bracket	12.6

It was also studied how the tooth displacements depend on the load size. With that aim in view the force and torque acting in the bracket were increased gradually maintaining the same ratio of the torque and force. Study results of the displacements of the vertex of the crown of the tooth are generalized in Fig. 11 where their dependencies on the quantity of impacting forces are presented.

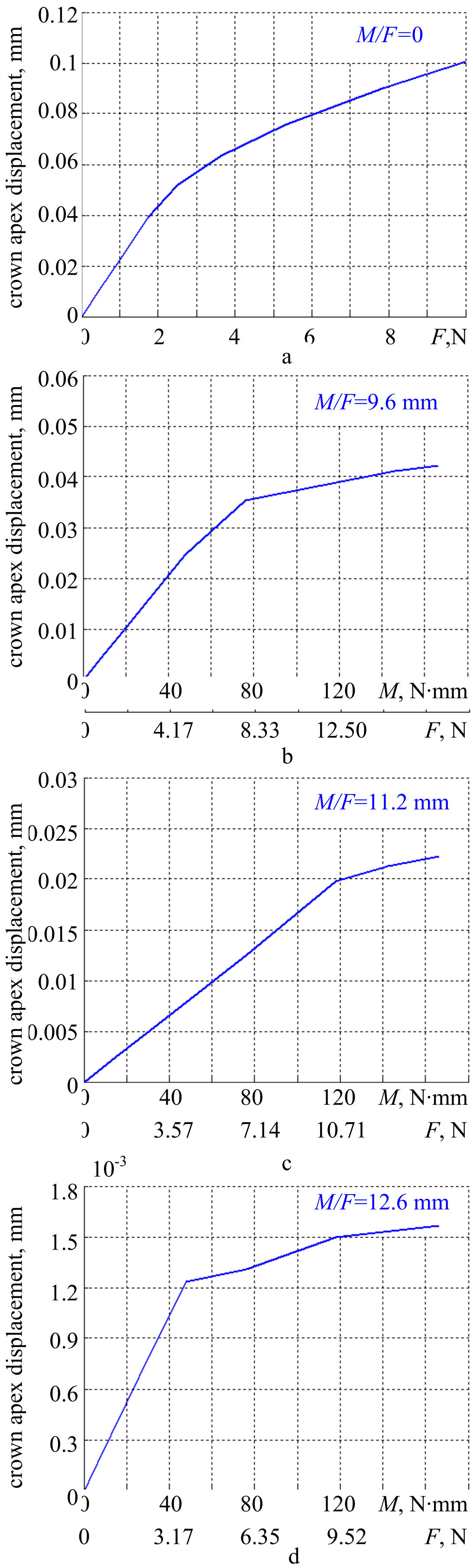


Fig. 11 Dependency of the apex of the crown of the tooth on the value of the tooth impacting load: a – simple tipping; b – controlled tipping; c – translation; d – lingual root movement

In the beginning the tooth moves proportionally to the size of the impacting force. Later when a certain value of the force is reached, the tooth displacements change very slightly. A force value that corresponds to the refraction point is regarded as optimal.

Forces up to the refraction point are usually used in orthodontics. It is not rational to use bigger forces because tensions in periodontal ligament increase significantly and the tooth displacements increase just slightly. According to the formed dependencies (Fig. 11) it is possible to establish what force is optimal for each type of movement (Table 3).

Table 3

Largest possible forces in different directions

Types of movement	Force and torque	
	F, N	*M*, N·mm
Simple tipping	2	0
Controlled tipping	7.29	70
Translation	10.71	120
Lingual root movement	3.17	40

It was found that the value of optimal force depends on what changes it causes in periodontal ligament. The force is different for various types of movement. It was established that the biggest forces could be used for the translation movement (force up to 10.71 N and the torque up to 120 N·mm) and the least ones – for a simple tipping of the tooth (up to 2 N).

It is possible to specify the established optimal values of forces only having established tension values in periodontal ligament and having evaluated if they do not exceed the permissible limit. In order to avoid undesirable effects, e.g. not to clutch blood vessels and to maintain activity of the periodontal ligament, the tensions in it are to be approximately equal to the capillary blood pressure (2000 - 2600 Pa).

5. Conclusions

Conclusions based on research results:

1. While analyzing biomechanical system of tooth-periodontal ligament-alveolar bone, it is necessary to estimate structural peculiarities and non-linear properties of the periodontal ligament. Shape and size of tooth and surrounding tissues can be established with precision enough for practical purposes by means of tomographical prints. Model of specific clinical situation of concrete patient can be built in this way.

2. Mechanical properties of the periodontal ligament and the shape of the tooth root determine the position of the tooth resistance centre. It was found that the centre of resistance is at the distance of 9.4 mm (60.3 %) of the root length above root apex.

3. The tooth under correction movement type depends of the ratio of the torque and force applied to the bracket by loop. On the basis of computed dependencies of position of the centre of rotation upon the ratio of the torque and force in the bracket proper forces and moments enabling to control the orthodontic tooth movements can be defined. Simple tipping of tooth results when the ratio of the torque and force in the bracket equals to zero. When this ratio is medium size, for example, 10 mm for canine, the movement is translational, and lingual root movement of canine takes place when this ratio exceeds 12 mm.

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DANTIES SLANKUMO SKAITINIS MODELIAVIMAS ESANT NETIESINĖMS PERIODONTO MEDŽIAGOS SAVYBĖMS

R e z i u m ė

Ortodontinis danties slankumas paprastai apibūdinamas dviem danties, kaip kieto kūno, centrų – pasipriešinimo ir sukimosi – padėtimis. Šiame darbe pateikiamas hipotetinis periodonto, kurio įtaka danties slankumui reikšmingiausia, medžiagos modelis. Naudotas netiesinis periodonto medžiagos modelis, pagrįstas netiesine įtempimų ir deformacijų tarpusavio priklausomybe. Tyrimui parinktas apatinio žandikaulio iltinis dantis. Šio danties baigtinių elementų erdvinis modelis ir buvo nagrinėjamas. Iš gautų rezultatų matyti, kad, esant netiesinėms periodonto medžiagos savybėms, iltinio danties pasipriešinimo centras pasislinko 0.4 mm danties viršūnės link, palyginti su rezultatais, gautais, kai periodonto medžiagos savybės tiesinės.

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NUMERICAL SIMULATION OF TOOTH MOBILITY USING NONLINEAR MODEL OF THE PERIODONTAL LIGAMENT

S u m m a r y

Orthodontic tooth movement is usually characterized by two centers: the centre of resistance and the centre of rotation. This paper reports on studies hypothetical mechanical representation of the periodontal ligament (PDL) which plays the most significant role in tooth mobility. The model assume a nonlinear material properties of PDL by means of nonlinear dependence of stresses on strains. Results were obtained by applying the finite element method (FEM) on a lower jaw canine. It was found that the nonlinear PDL locate centre of resistance apically 0.4 mm in comparison with those obtained with linear PDL.

Й. Данелите, Р. Гайдис

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПЕРЕМЕЩЕНИЙ ЗУБА ПРИ НЕЛИНЕЙНЫХ СВОЙСТВАХ ПЕРИОДОНТА

Р е з ю м е

Ортодонтическое перемещение зуба, как твердого тела, определяет положение двух центров – сопротивления и вращения. В этой работе представлена модель периодонта, который существенно влияет на перемещения зуба. Использована нелинейная модель периодонта, описанная нелинейной зависимостью между напряжениями и деформациями. Исследован нижний клык. Его конечноэлементная модель и была оставлена. Из полученных результатов следует, что при нелинейных свойствах периодонта центр сопротивления клыка смещается на 0.4 мм вверх, чем при линейных свойствах периодонта.

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