Biomechanical finite-element investigation of the applicability of the orthodontic concept of the center of resistance.

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***Abstract*—Orthodontic tooth movement is achieved by application of forces to teeth. The objective of this study was to estimate applicability of the concept of the center of resistance and to offer more accurate method to describe the process of initial movements of teeth. A three-dimensional finite-element model of a lower human mandible was developed on the basis of computer tomography image data.**

Keywords: tooth movement,sliding mechanics, finite-element method, center of resistance.

I. INTRODUCTION

Orthodontic treatment is intended to correct or prevent teeth position disorder and malocclusion. Fundamental concept of the orthodontic treatment is practical application of biomechanical principles [1]. Treatment process consists of application of forces to teeth; forces are generated by various orthodontic appliances. Biological process, occurring in dentition under the influence of orthodontic forces, results movement of teeth through their supporting bone. The cells of the periodontal ligament (PDL) which respond to the applied forces are insensitive to the bracket design, wire shape, or alloy of the orthodontic appliances – their activity is based solely on the stress-strain state occurring in their environment [2]. The treatment success depends considerably on the accuracy of the applied forces choice. In complex clinical cases it is difficult to provide efficient treatment without preliminary analysis of patient's dentition biomechanical state.

Process of orthodontic treatment was considered in this work as biomechanical process and simulated using contemporary computer systems. To determine type of teeth movement under applied forces, conception of the center of resistance (CR) extensively used [3] [4]. The center of resistance is considered as analogue of center of mass but for body whose movements are limited. If resultant of system of forces applied to body passes through CR and moment reduced to CR equals to 0 that body will move transitional by the line of load, without rotation. Introducing CR, it is possible to represent that object of investigation does no exist, and its mass is concentrated at one point. In the sequel, we can determine movement of object by reducing forces to this point. There are many studies aimed to determine the exact location of the CR by various theoretical and experimental methods, substantially using idealized models. They concluded that the center of resistance for single-rooted tooth with normal alveolar bone levels is about one-fourth to one-third the distance from the cementoenamel junction to the root apex [3-7].

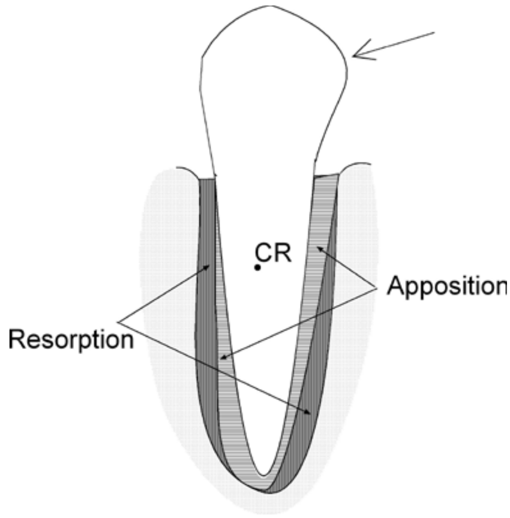

Fig. 1 Biomechanical concept of the tooth movement

Articles pointing to limitations in applicability of the conception of CR appear recently [8][10]. In this investigation we check the results obtained using the concept of the CR and we propose a new method that simulates a process of tooth movement more precise.

The study was performed using the finite-element method [11] [12]. Finite-element method is a very powerful method to solve complex stress-strain problems in the mechanics of solids. It consists in dividing geometrically complex structure into simple geometric elements that are interconnected. This method allows for exact modeling of tooth and PDL behavior under the loads.

II. Materials and methods

To estimate applicability of the conception of CR, general case of object movement under the influence of the forces was regarded. As PDL received almost all of the forces applied to teeth, it is possible to think that stiffness of teeth is much greater that stiffness of PDL. Therefore teeth may be regarded as rigid bodies [13]. In this case it is possible to reduce all of the forces applied to the tooth to one point and describe their as load vector $\vec{F}$ consisting of six components (3 projections of force and 3 moments). Movement of tooth can be described as displacement vector $\vec{u}$, the same dimension (3 for transition and 3 for rotation). We can consider these vectors as linearly associated because of displacements are small under initiation. It is possible to represent this relationship as flexibility matrix $[D]$ that have dimension 6x6.

$$\vec{u} = [D] \cdot \vec{F}$$

Components of $[D]$ can be determined by solving 6 test problems: determine vector of movements under the influence of unit loads, alternately applied to each direction (direct stiffness method). We can found movements of teeth by multiplying flexibility matrix in some point to vector of loads that contains all forces and moments applied to this point. Similarly, inverse problem can be solved: we can found loads vector to produce specified movement by multiplying inversed flexibility matrix to vector of movements.

$$\vec{F} = [D]^{-1} \cdot \vec{u}$$

At the location of the CR, unit loads will produce movements only by direction of load. Thus, flexibility matrix should be appeared as diagonal matrix:

$$[D] = \begin{bmatrix} d_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & d_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & d_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & d_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{66} \end{bmatrix}$$

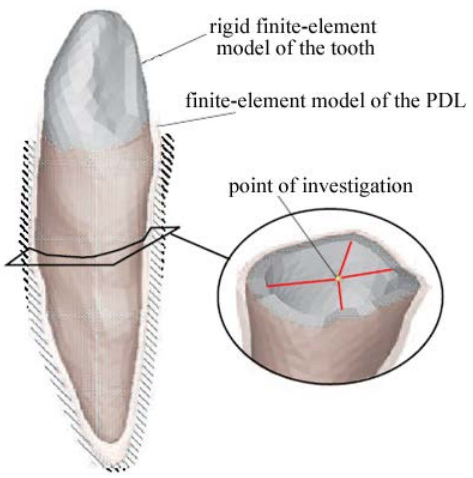

Fig. 2 Finite-element model of the tooth and PDL

Note that quantity values of forces and displacements must be nondimensionalized with respect to characteristic properties of a model.

It is possible to verify the applicability of the conception of CR by means of the three-dimensional finite-element method. Geometry of the teeth was derived from digital computer tomographic scan data. A segment of a lower human mandible was scanned with a CT scanner. Image processing software (Amira, Mercury Computer System, USA) was used to generate three-dimensional solid models of the alveolar bone and teeth. The solid model was imported into HyperMesh (Altair Engineering, USA) and meshed with 8-node brick element. The PDL finite elements were modeled as the space between the alveolar socket and root of tooth. Contemporary algorithms of image segmentation and meshing allow automate these operations [14-15], because the real clinical case contains much of data. The finite-element model was imported into ANSYS software (ANSYS Inc., USA) for analysis.

Central incisor was used as an object for investigation. Its model has been separated from mandibular finite element model. It is possible to consider that tooth and bone are rigid bodies because PDL receives almost all the loads applied to tooth. Therefore tooth was modeled by one layer of rigid tetrahedral finite elements that fits to solid model. Investigated point was connected to rigid model of tooth by 4 beam elements (BEAM4) width 6 degrees of freedom at each node. Location of investigation point has been selected as location of CR commonly used by dentists: 0.4 times the root length measured apical to the level of alveolar crest.

In the present analysis, all the materials of the model were assumed to be isotropic and elastic because of small displacements. Material behavior of PDL was considered to be with a Young’s modulus of

0.17 MPa and Poisson's ratio of 0.3. These values are based on previous studies [2].

III. RESULTS

Unit loads were applied to designed model at the investigated point. Components of flexibility matrix $[D]$ were determined using direct stiffness method.

$$[D] = 10^{-6} \cdot \begin{bmatrix} 38.97 & -3.45 & -2.36 & -9.75 & -9.51 & 0.66 \\ -3.45 & 36.16 & 4.97 & 9.72 & 9.80 & -1.44 \\ -2.36 & 4.97 & 48.3 & -5.05 & -4.76 & -0.51 \\ -9.75 & 9.72 & -5.05 & 232 & -148 & -172 \\ -9.51 & 9.80 & -4.76 & -148 & 298 & 236 \\ 0.66 & -1.44 & -0.51 & -172 & 236 & 746 \end{bmatrix} \frac{mm}{H}$$

It appears that values located at the main diagonal of the flexibility matrix are significantly greater than other values. This fact shows that conception of CR grants approximately correct solution. But moments applied to CR activated rotation in direction that is different from direction of moments. So applicability of conception of CR can give very inaccurate solution in some cases. For example, moment of a couple about the CR can activate rotation around an axis different that axis of a moment. Use of mentioned way to calculate tooth movements through flexibility matrix can provide more correct results.

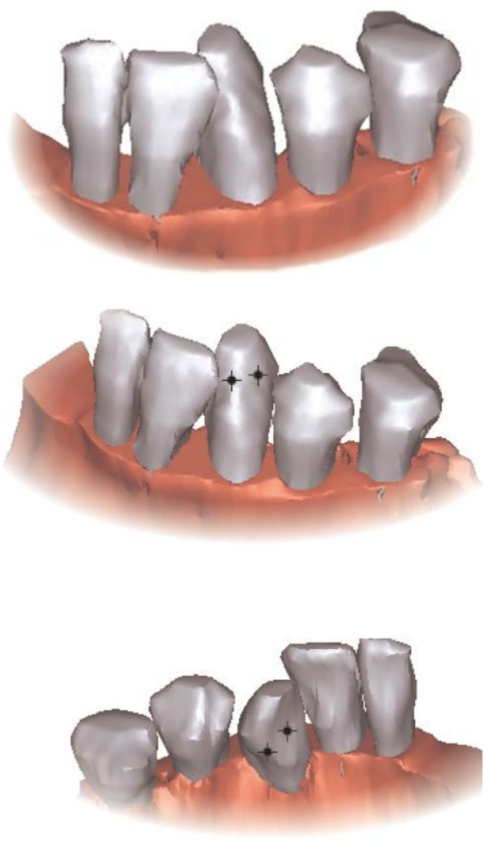

Fig. 3 Model of the clinical case and locations of the recommended points of anchoring.

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To confirm this method, example of real clinical case was taken. In case presented at Fig. 3, one of teeth has incorrect position. To fix this defect it is required to determine location of anchoring of rubber rods that can rotate tooth to correct position.

This case has been modeled mentioned way. Flexibility matrix at the CR was determined. Displacements vector was designated to rotate tooth around an occlusal axis. Then loads vector has been found. Loads were resolved to a couple applied to teeth and recommendations to doctor has been presented.

IV. CONCLUSIONS

It is possible to solve the problem of modeling and analyzing initial tooth displacements for each patient individually. Use of contemporary computational systems can automate most of operations.

Developed methodology allows describing processes of force and deformation interaction of the biomechanical system's elements and making recommendations to clinician in order to reduce risks of complications and improve efficiency of treatment.

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