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STRESS ANALYSES IN DENTAL BIOMECHANICS

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ABSTRACT
The aim of this work was to determine stress distribution in two different examples of oral systems: human mandible during simulation of mastication force loading, and human upper canine teeth loaded with orthodontic force due to mobile or fixed braces.
The 3D geometrical model of mandible was reconstructed from dry human mandible. Analytical and finite-element methods were used for the determination of mandible loading and stress distribution.
An upper canine extracted for periodontal reasons served as a pattern for the design of a CAD model. The tooth was modelled with its basic parts: enamel, dentin, periodontal ligament and cortical and spongy bone as a place where the tooth is anchored in the jaw. The analyses of stress were performed using the finite-element method.
The obtained results may be applied in practice, and the finite-element method represents efficient tool in estimating stresses in dental biomechanics.
Keywords: dental biomechanics, human mandible, single root tooth, finite-element method

1. INTRODUCTION
The knowledge of biomechanical behaviour of the human mandible and teeth is of great importance in the analyses of stress and strain distribution due to mastication and biting, as well as in various clinical situations such as orthodontic treatment, dental implants and treatment of maxillo-facial trauma. Numerical investigations using a finite-element analysis (FEA) are becoming the most advantageous choice in biomechanical studies of oral systems. FEA requires the exact parameters of material to be known, as well as the geometry of the object in question. The problems are the lack of information on the properties of the material, the uncertainty of correct load distribution and the assignment of proper boundary conditions.
The aim of this work was to predict the complex biomechanical behaviour of human mandible and teeth under mechanical loading. Two independent examples were used in determining stress distribution.

2. METHODS AND RESULTS
Stress distribution was determined in two cases: human mandible during simulation of mastication force loading, and human upper canine loaded with force due to orthodontic braces.

2.1. Human mandible loaded with mastication force
A dry mandible of a man (aged 30 years) was scanned using Cyberware 3030 3D laser digitizer [1]. As a result of scanning, a cloud of points written in ASCII code was made. These data were used for the definition of 3D mandible model in computer program Catia. The obtained 3D mandible model was in good qualitative agreement with the original. Figure 1 represents the cloud of points and the 3D

model designed in Catia. Two different kinds of bones were distinguished in the mandible: cortical or compact bone in the outer part of bones, and cancellous or spongious bone in the inner part. The 3D model of the mandible consisted of cortical and spongious bones with different isotropic material properties [1]. The FEM analysis using tetrahedron finite elements was performed. The model was loaded with force on lower canine in the magnitude of 127 N, which simulates the force of bite. The model was restrained at the head with reactive forces acting in temporo-mandibular joint. Due to simplification, muscular forces were neglected. Figure 3 shows boundary conditions and loading acting on the mandible. Figure 4 represents mandible displacement and stress distribution. Results were compared with a simplified analytical model shown in Figure 2, and good agreement was noticed [1].

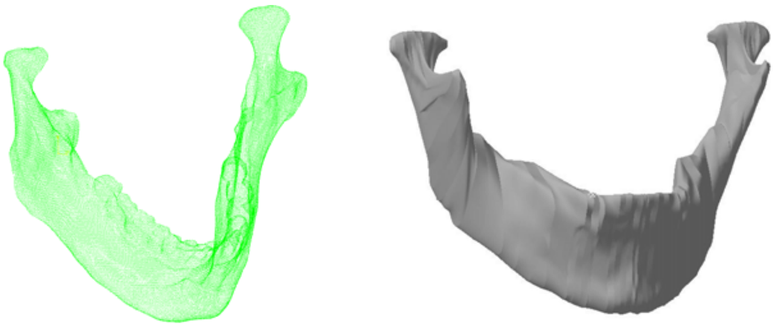

Figure 1. Cloud of points and 3D mandible model designed in Catia

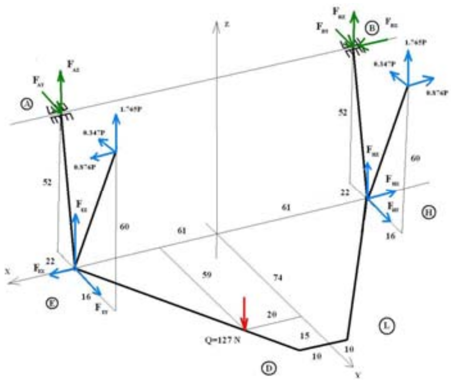

Figure 2. Analytical model of mandible

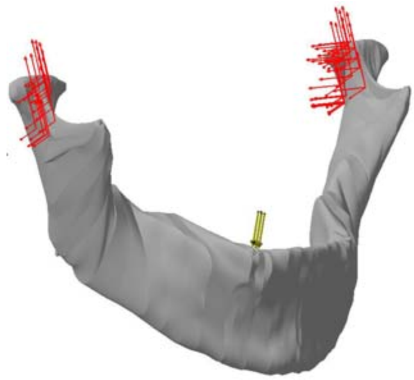

Figure 3. 3D mandible model with boundary conditions and loading

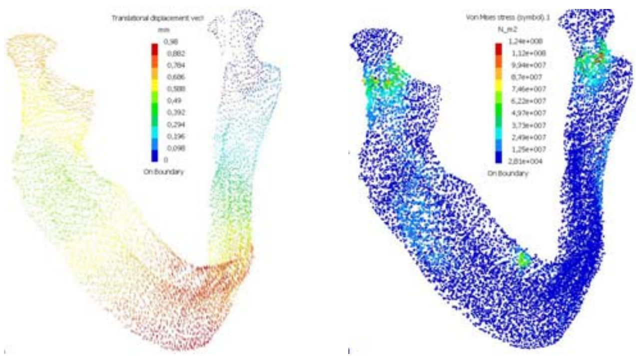

Figure 4. Displacements and stress distribution

2.2. Human upper canine loaded with orthodontic force

While orthodontic braces are being used, biomechanical forces are generated, resulting in translations and/or rotations of the tooth. In this analysis, the tooth was designed with its basic parts, i.e. enamel, dentin, periodontal ligament (PDL) and bone, in the CAD program. The term bone denotes the part of the bone where the tooth is anchored in the jaw. The bone consists of two parts: cortical bone, the compact outer part of osseous tissue, and cancellous bone, the spongy, inner part. PDL attaches the tooth to the alveolar bone.

The upper canine extracted for periodontal reasons served as a pattern for the design of a CAD model. After the cross sections had been extracted, the three-dimensional model was defined from the curves of the cross-sections of the tooth, using the lofting method in the program Catia (Figure 4) [2].

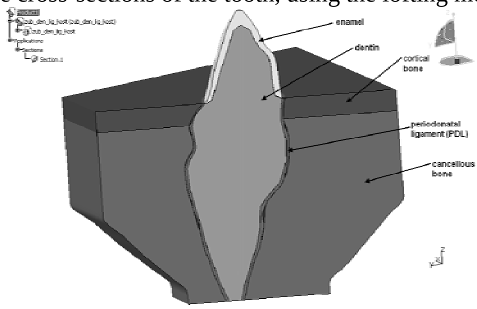

Figure 5. 3D tooth model designed in Catia

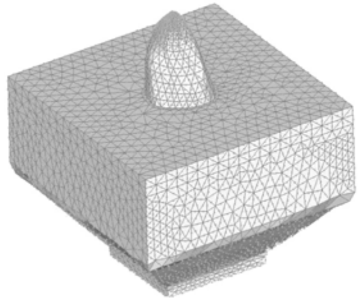

Figure 6. Finite-element mesh of the tooth

After designing a model of the tooth and the surrounding bone, the FEM analysis using tetrahedron finite elements was performed (Figure 6). A finite-element mesh was made using MSC.Nastran, and the analysis was performed by ABAQUS/Standard 6.5-1. The mechanism of transferring the load from the braces to the tooth was simplified and orthodontic forces were depicted as concentrated. The point load with the magnitude of 5 N was applied at four different distances from the peak of the tooth: 1.4 mm, 2.4 mm, 3.4 mm and 4.4 mm. Boundary conditions were defined as clamped on the bone, thus simulating the connection of the bone to the rest of the mandible. The analysis of stress in the tooth is very complex due to the heterogeneous tooth material and the irregularity of tooth contours resulting in very complex morphology of the object. Properties of the material in some parts of the tooth were determined based on the values available in literature, with every part having significantly different mechanical properties [2,3,4,5]. Analyses were performed with isotropic and orthotropic material properties. The orthotropic properties available in the literature have been defined for dentin, cortical bone and cancellous bone. Therefore, in the first analysis, all parts of the tooth had isotropic material properties, while in the second analysis, the cortical bone, the cancellous bone and the dentin had orthotropic properties along with isotropic ones used for enamel and PDL.

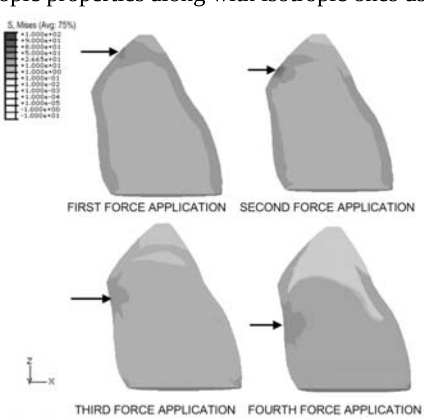

Figure 7. Von Mises (HMH) equivalent stresses for the tooth crown (isotropic properties)

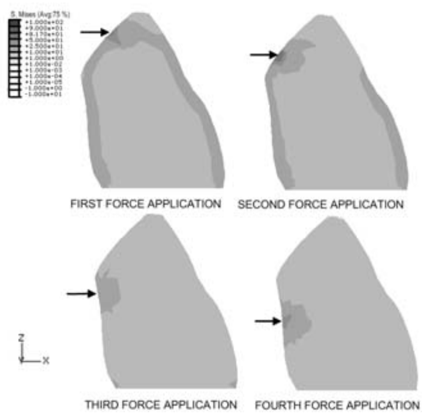

Figure 8. Von Mises (HMH) equivalent stresses for the tooth crown (orthotropic properties)

Figures 7 and 8 show the results in the form Von Mises (HMH) equivalent stress for the tooth crown. The equivalent stress is highest at the point of force application, and its intensity decreases in concentric circles. The maximum stress occurs at the point of the first application of force (61.35 MPa in the analyses with isotropic properties, 81.7 MPa in the analyses with orthotropic properties), and the minimum stress occurs at the point of the fourth application of force (26.65 MPa for isotropic and orthotropic properties). Figures 9 and 10 show the cross-section segments of the tooth, with the displacement equal to zero. Circular zones of the tooth represent the centre of rotation. The centre of rotation is the area around which the tooth rotates/translates during the application of orthodontic force. The centre of rotation is not stationary and it depends on each particular load. In the analyses with isotropic and orthotropic properties, the largest displacements were at the place of the first application of force, but in the analysis with isotropic properties the displacement was larger than in the analysis with orthotropic properties. Using isotropic properties, larger displacements were also noted at all other points of force application. It can be concluded that the definition of material properties as isotropic/orthotropic has an important effect on displacement results, differing from stress results.

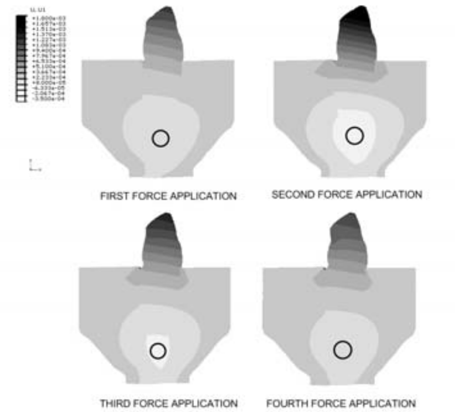

Figure 9. Tooth displacement (isotropic properties)

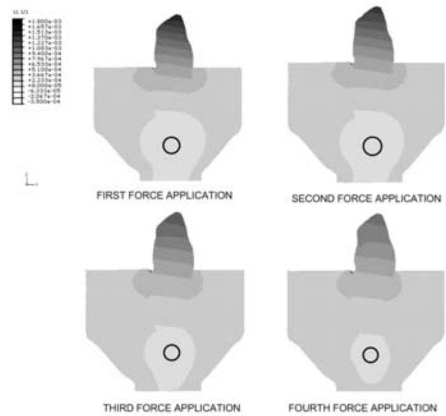

Figure 10. Tooth displacement (orthotropic properties)

3. CONCLUSION

A proper knowledge of the biomechanics of the mandible is essential to improve orthodontic and temporo-mandibular joint treatments designed to solve specific pathology and disorders.

Based on the results of stress analysis of the tooth, it can be noticed that there are no significant differences in equivalent stress values when comparing the analysis with isotropic material properties and the analysis with orthotropic material properties. There are small deviations in the first case of load (with the first application of force), which are not noticed in the other three cases of load. The proper definition of orthodontic forces (magnitude and point of force application) is important for determining the centre of rotation. Due to the application of braces to the teeth, PDL has to weaken its connections, which causes bone remodelling at the place of tooth translation/rotation.

The finite-element method may be a valuable and efficient tool in addressing the aforementioned biomechanical problems. Nevertheless, experimental verification of these results should be performed in order to make them more reliable.

4. REFERENCES

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