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Finite element investigation of human maxillary incisor under traumatic loading: Static vs dynamic analysis

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ABSTRACT

Background and objective: Traumatic loading is the main form of injury sustained in dental injuries. In spite of the prevalence of dental trauma, little information is available on traumatic dental damage and the evaluation of tooth behavior under traumatic loading. Due to the short period of traumatic loading, at first sight, a dynamic analysis needs to be performed to investigate the dental trauma. However, it was hypothesized that dental traumatic loading could be regarded as quasi-static loading. Thus, the aim of the present study was to examine this hypothesis.

Methods: Static and dynamic analyses of the human maxillary incisor were carried out under traumatic loading using a 3D finite element method. Also, modal analysis of the tooth model was performed in order to evaluate the assumption of the dental traumatic loading as a quasi-static one.

Results: It was revealed that the static analysis of dental trauma is preferred to the dynamic analysis when investigating dental trauma, mainly due to its lower computational cost. In fact, it was shown that including the inertia of the tooth structure does not influence the results of the dental trauma simulation. Furthermore, according to the modal analysis of the tooth structure, it was found that the mechanical properties and geometry of the periodontal ligament play significant roles in the classification of dental traumatic loading as a quasi-static one, in addition to the time duration of the applied load.

Conclusions: This paper provides important biomechanical insights into the classification of dental loading as quasi-static, transient or impact loading in future dental studies.

1. Introduction

Dental trauma is one of the most common incidents in the field of dentistry. The impact on teeth during falls, motor vehicle accidents, sports, and assaults that causes injury to the dental structure is called dental trauma [1–4]. According to clinical studies, the most vulnerable teeth to traumatic injuries are the maxillary central incisors [1,2]. Although several experimental and numerical studies in the dental biomechanics field have been conducted under physiological and orthodontic loading conditions in the last half century, in spite of the prevalence of dental trauma, accurate biomechanical characteristics of dental injuries and the reactions of the surrounding tissues are still unknown [5–8].

On the other hand, the study of dental trauma and assessment of its relevant factors via *in vivo* or *in vitro* experiments are very difficult to perform. Other methods such as finite element (FE) have been developed for better investigation of traumatic dental damage and the evaluation of tooth behavior under traumatic impact. Because of the short duration of traumatic loading, at first sight, the study of dental trauma should be regarded as a dynamic analysis. According to the literature review, in most FE models of dental trauma [5–8], transient dynamic analysis of the maxillary central incisor has been conducted under impact loading in different situations using either 2D or 3D models. However, the hypothesis of this study was that the dental traumatic loading could be regarded as quasi-static loading. Indeed, it was hypothesized that the classification of dental trauma loading into quasi-static, transient or impact loading would be dependent on the ratio of the time duration of the applied load to the longest natural period of tooth structure.

The purpose of the present study was, hence, to assess this hypothesis (i.e. regarding dental traumatic loading as quasi-static). First, both static and dynamic stress analyses of the human maxillary central incisor under traumatic loading were carried out using a 3D FE model. Then, in order to confirm or reject the proposed hypothesis, modal analysis of the incisor tooth model was

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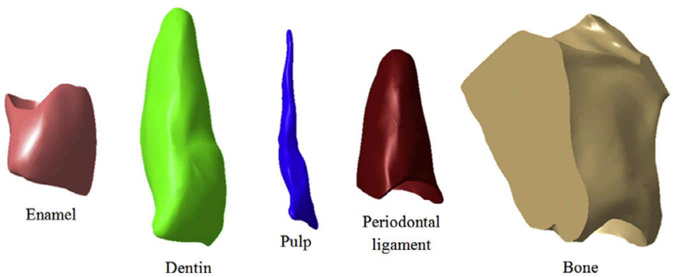

Fig. 1. An illustration of the model components.

conducted to determine the natural frequencies of the tooth structure. It should be pointed out that if the ratio of the duration of the applied load to the longest natural period of the structure is more than about four, static analysis can be performed and the loading would be regarded as quasi-static [9,10].

2. Methods

2.1. Model preparation

The maxillary central incisor is the most vulnerable tooth to traumatic injuries [1,2], therefore, it was selected for the FE modeling under traumatic impact loading. To this end, image acquisition in TIFF (Tag Image File Format) format was carried out with a micro-computed tomography (micro-CT) (SMX-225CT-SV, Shimadzu, Japan) under the following acquisition parameters: pixel matrix, 512 × 512; tube voltage, 70 kV; tube current, 50 μA; slice thickness, 0.09 mm. Each voxel consisted of a 0.09 mm isotropic cube. In order to obtain a 3D geometric model of the human maxillary incisor, first, the images were imported into the MIMICS software (MIMICS 10.1, Materialise N.V., Leuven, Belgium) for image segmentation. Secondly, cloud points of the extracted enamel, dentin, pulp, and bone data were separately exported in STL format and finally transferred to CAD software (CATIA V5, Dassault Systèmes, Vélizy-Villacoublay, France) in order to patch the surface and reconstruct the solid model. The final model included the enamel, dentin, pulp, periodontal ligament (PDL), and a part of the maxillary bone, as presented in Fig. 1. Based on the micro-CT data, the bone was not differentiated into cortical and cancellous bone; moreover, cementum could not be distinguished from dentin. Because of the impossibility of direct modeling of the CT image, PDL (with an average thickness of 0.25 mm) was created from the available gap between the dentin and bone. In this model, the length of the tooth was about 27.5 mm, the crown was 11.9 mm, and the root was 15.6 mm, of which 14.5 mm was inserted in the bone.

A mesh convergence test was carried out to determine the optimum number of elements. Accordingly, the model in the FE simulations (ABAQUS 6.3, Dassault Systèmes, Vélizy-Villacoublay, France) was discretized into 192,002 nodes and 137,652 quadratic tetrahedral elements.

2.2. Material properties

The physical and mechanical properties of different tissues of the tooth, PDL, and maxillary bone are listed in Table 1 [11,12]. All the properties were considered to be homogenous, isotropic and linear elastic. Although the enamel, dentin, and bone have anisotropic properties, the dependence of their mechanical properties (elastic modulus and Poisson's ratio) on direction is not considerable [13,14]. Furthermore, due to the short time duration of traumatic loading, the viscoelastic properties of PDL were neglected. Recent works [15,16], however, have declared low energy dissipation in high loading rates supporting the latter assumption

Table 1
Physical and mechanical properties of the components of the model.

Component	Density (Kg/m^3)	Elastic modulus (GPa)	Poisson's ratio
Enamel	2800	84.1	0.3
Dentin	1960	18.3	0.31
Pulp	1000	0.002	0.45
PDL	1040	0.01	0.45
Bone	1300	2	0.3

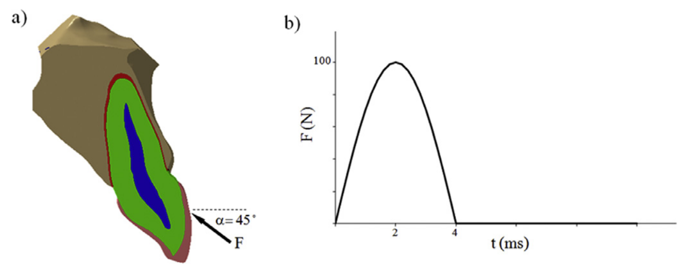

Fig. 2. (a) Schematic drawing of the situation of traumatic loading; (b) Force-time history applied to the maxillary central incisor.

of the present study. Indeed, elastic modeling of the PDL is suitable for describing its mechanical response at high loading rates [17,18]. Thus, in this study, the elastic modulus of the PDL was considered to be 10 MPa, whereas, it has been reported from 0.01 to 100 MPa in numerical studies [19]. Also, since the maxilla was considered as a single material, the average elastic modulus of 2 GPa for the maxillary bone was assumed [20,21].

2.3. Analyses

2.3.1. Stress analysis

Based on earlier studies, numerical analyses of dental trauma have been performed via transient dynamic analysis [5–8]. Nevertheless, the hypothesis of this study was that the results of the static and dynamic analyses of dental trauma would be similar. For this purpose, the static and dynamic numerical simulations of dental trauma were carried out under the same conditions. Accounting for the large deformation of PDL, nonlinear analysis in both the static and dynamic simulations was activated. Also, both explicit and implicit time integration schemes for dynamic simulation of the dental trauma were considered. The traumatic loading condition of the present study was assumed as a concentrated force representing a collision between the maxillary incisor and a hard object with high elastic modulus. As shown in Fig. 2, a sinusoidal force was applied on the labial surface of the enamel in its central region over a period of 4 ms with an arbitrary peak of 100 N, angled at 45°, to simulate the static and dynamic analyses of traumatic force [6,7,22]. Degrees of freedom of the two cutting faces of the maxilla (parallel to the sagittal plane) were also constrained in the normal direction.

2.3.2. Modal analysis

To examine the similarity between the results of the static and dynamic analyses of dental trauma, the modal analysis of the FE model based on the material properties of Table 1 was conducted in order to determine the natural frequencies and the natural mode shapes of the tooth structure. It is important to note that if the ratio of the time duration of the applied load to the longest natural period corresponding to the first natural frequency of the structure is less than about one-fourth, the loading should be classified as a shock or impact loading, and transient dynamic analysis would then be required. If the ratio is more than about four, it would be adequate to perform a static analysis and to