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Efficient 3D finite element analysis of dental restorative procedures using micro-CT data

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ABSTRACT

Objectives. This investigation describes a rapid method for the generation of finite element models of dental structures and restorations.

Methods. An intact mandibular molar was digitized with a micro-CT scanner. Surface contours of enamel and dentin were fitted following tooth segmentation based on pixel density using an interactive medical image control system. Stereolithography (STL) files of enamel and dentin surfaces were then remeshed to reduce mesh density and imported in a rapid prototyping software, where Boolean operations were used to assure the interfacial mesh congruence (dentinoenamel junction) and simulate different cavity preparations (MO/MOD preparations, endodontic access) and restorations (feldspathic porcelain and composite resin inlays). The different tooth parts were then imported in a finite element software package to create 3D solid models. The potential use of the model was demonstrated using nonlinear contact analysis to simulate occlusal loading. Cuspal deformation was measured at different restorative steps and correlated with existing experimental data for model validation and optimization.

Results. Five different models were validated by existing experimental data. Cuspal widening (between mesial cusps) at 100 N load ranged from 0.4 μm for the unrestored tooth, 9–12 μm for MO, MOD cavities, to 12–21 μm for endodontic access cavities. Placement of an MOD adhesive restoration in porcelain resulted in 100% cuspal stiffness recovery (0.4 μm of cuspal widening at 100 N) while the composite resin inlay allowed for a partial recuperation of cusp stabilization (1.3 μm of cuspal widening at 100 N).

Significance. The described method can generate detailed and valid three dimensional finite element models of a molar tooth with different cavities and restorative materials. This method is rapid and can readily be used for other medical (and dental) applications.

1. Introduction

It is a well-established claim that mechanical testing is of paramount importance, not only in aerospace, civil engineering and the automotive industry, but also in health care. The field of biomedical research raises specific problems due to the fact that today's research may prove extremely expensive and ethically questionable when performed on live subjects. To limit the costs and risks involved in live experiments, virtual models and simulation approaches have become unavoidable [1]: an iterative optimization of the design of the experiment is performed on the computer and is seen in virtual prototyping and virtual testing and evaluation; after this iterative step, when the best design has been refined, the actual experiment

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is conducted. The value is that the modeling and simulation step saves time and money for conducting the live experiment or clinical trial.

Yet dental research seems to make very little use of virtual models, such approaches representing a minor part of the scientific publication volume. In finite element (FE) analysis, a large structure is divided into a number of small simple-shaped elements, for which individual deformation (strain and stress) can be more easily calculated than for the whole undivided large structure. By solving the deformation of all the small elements simultaneously, the deformation of the structure as a whole can be assessed. Using the traditional biophysical knowledge database in a rational validation process [2], the use of FE analysis in dental research has been significantly refined during the last decade [3–10]. Nowadays, experimental–numerical approaches undoubtedly represent the most comprehensive in vitro investigation methods in restorative dentistry [9,10]. They allow the researcher (1) to reduce the time and cost required to bring a new idea from concept to clinical application, (2) to increase their confidence in the final concept/project by virtually testing it under all conceivable loading conditions.

Because teeth and bones cannot be assimilated to a simplified geometric representation but have anatomical shapes and a layered structure, sophisticated techniques have been developed to refine geometry acquisition, such as the recreation and digitization of planar outlines of the spatial anatomy [11,12]. This is often the most time-consuming step for the modeler. In addition, this process is prone to errors and simplifications which may induce faulty predictions. For this reason, patient's geometry-based meshing algorithms have already been proposed to generate complex solid models of bones as for example the CT scan-based FE model [6]. Similar approaches can be used with microscale CT scanner for the simulation of small objects like teeth, dental implants and dental restorations [13]. However, considerable work is still required in order to obtain congruent parts (sharing the exact same geometry at their interface) and smooth relationships between the different 3D objects (enamel, dentin, restoration). By the same token, modification of a given parameter, like for instance variations in restoration size, often requires the realization of a new and separate model, including the time-consuming geometry acquisition.

The aim of the present study is therefore to propose a further development to facilitate and accelerate geometry acquisition/modification during the fabrication of FE models of tooth restorations. The presented method is based on stereolithography (STL) and surface-driven automatic meshing. In this innovative approach, validated by cuspal flexure measurements, the model is built in multi-parts (using segmentation and Boolean operations with CAD objects) based on the geometry of the unaltered tooth. The same method can also be used to create patient-specific models from any other body part using either MRI or CT data.

Table 1 – Sequential procedure, computer software and times used to generate the 3D FE tooth model

1. Micro-CT scan data (stack of bitmap files) from Skyscan 1072 (Skyscan)

Scan time: 2 hours for 1128 slices

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2. Segmentation of enamel and dentin into 3-D objects (Mimics 9.0 + Remesh module, Materialise)

Generation of triangulated stereolithography files (STL) for enamel and dentin

Remeshing of STL files (triangle reduction, triangle quality improvement)

Accomplished in ca. 90 minutes

↓

3. STL files treatment (Magics 9.9, Materialise)

Boolean operations to ensure dentinoenamel mesh congruence

Boolean operations with CAD objects to simulate successive restorative procedures

Accomplished in ca. 30-60 minutes per model (including all Boolean operations)

↓

4. Automatic generation of volumetric mesh (MSC.Marc/Mentat 2005, MSC.Software)

Attribution of material properties and boundary conditions

Linear or nonlinear finite element analysis (e.g. contact analysis)

Accomplished in ca. 30-60 minutes per model (including 17 minutes to run the analysis)

The tooth model may be accomplished by a trained operator in less than a workday (depending of the complexity of the parts and general goal of the project). The same approach is applicable to other disciplines (orthodontics, orthopedic surgery, etc.) to generate patient-specific models from MRI or CT-scan data.