

Three-dimensional simulation of human teeth and its application in dental education and research

Maryam Koopaie*¹, Sajad Kolahdouz²

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Abstract

Background: A comprehensive database, comprising geometry and properties of human teeth, is needed for dentistry education and dental research. The aim of this study was to create a three-dimensional model of human teeth to improve the dental E-learning and dental research.

Methods: In this study, a cross-section picture of the three-dimensional model of the teeth was used. CT-Scan images were used in the first method. The space between the cross-sectional images was about 200 to 500 micrometers. Hard tissue margin was detected in each image by Matlab (R2009b), as image processing software. The images were transferred to Solidworks 2015 software. Tooth border curve was fitted on B-spline curves, using the least square-curve fitting algorithm. After transferring all curves for each tooth to Solidworks, the surface was created based on the surface fitting technique. This surface was meshed in Meshlab-v132 software, and the optimization of the surface was done based on the remeshing technique. The mechanical properties of the teeth were applied to the dental model.

Results: This study presented a methodology for communication between CT-Scan images and the finite element and training software through which modeling and simulation of the teeth were performed. In this study, cross-sectional images were used for modeling. According to the findings, the cost and time were reduced compared to other studies.

Conclusion: The three-dimensional model method presented in this study facilitated the learning of the dental students and dentists. Based on the three-dimensional model proposed in this study, designing and manufacturing the implants and dental prosthesis are possible.

Keywords: Three-Dimensional Modeling, Dental Education, Finite Element Analysis.

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Introduction

Nowadays, the status of the oral health is one of the great challenges in the field of health, treatment and medical education. In this context, specialized training of the staff and students is of prime importance. One of the most important educational needs of the dental students is evaluation of patients' teeth and oral cavity. In this study, the teaching principles of prevention, diagnosis and treatment of the oral cavity disorders were the learning priorities. During dentistry education, students practice many dental procedures. The traditional approach in dentistry education is based on the treat-

ment of those patients who are referred to dental schools or based on practicing on the standard plastic teeth. Difficulty of regular access to human samples and deficiency of expert observers are the limitations of traditional methods. This study found that using the virtual three-dimensional tooth model appeared to be more efficient than plastic models (1).

Using the virtual three-dimensional model of the teeth and gums, as well as enhancing the quality of dental education will reduce learning time. Dentists need models for frequent modifications to reach the best prosthesis and to have a more accurate ex-

¹. (Corresponding author) Assistant Professor, Department of Oral and Maxillofacial Medicine, School of Dentistry, Tehran University of Medical Sciences, Tehran, Iran. m-koopaie@tums.ac.ir & maria_koopaie@yahoo.com

². Master of Science in Mechanical Engineering, Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran. sajjadkolahdouz@gmail.com

amination, and appropriate design. Dental modeling and simulation to verify the accuracy of the prostheses and to meet dental students' training needs seems irrefutable (2,3). Three-dimensional models in various aspects of dental treatment, including oral surgery, implants and orthodontics can be very useful (4). Most common problems in the field of dentistry are dental decays and periodontal diseases (5). Providing a high-resolution three-dimensional model that consists of all the aspect of oral cavity could be very effective (6).

Using a three-dimensional model can be an alternative method for the conventional non-imaging method, which reduces costs, time and increases the compliance of a final prosthesis. The purpose of this study was to present a three-dimensional model of the teeth to be used in the field of education, research and treatment. Furthermore, this method could be effective in reducing the educational cost and time, and decreasing the experimental test for the researchers (3). Reverse engineering is an important technique to manufacture the industrial products, and may be used in dental modeling (7-11). Accuracy and precision are the challenges of reverse engineering of dental modeling. One of the applications of modeling is using the model in the finite element analysis (2,7-10). A more precise-model will be more applicable in the finite element analysis.

The sectioning images are used for reverse engineering, but this method is expensive, and time consuming (12,13). Recently, the use of Cone Beam Computed Tomography (CBCT) and Multi-Slice CT (MSCT) has reduced problems related to teeth modeling (14). One of the most important challenges in three-dimensional modeling is the relationship between CT-Scan images and the modeling software (6,15). Because of the complex features of the tooth structure, different methods have been used for dental modeling (16). One of these methods is based on the mesh generation algorithm, the graphic effects of which would be relatively acceptable. Although

this method is cost-effective, it appears to have major weaknesses when it comes to different structures of the teeth (enamel and dentine), and material properties definition (2).

Another approach is based on the Voxel method in which material properties and different teeth structures are defined. Although the apparent looks of the mesh model are better, the Voxel model is more suitable for the dental finite element analysis due to the definition of the properties of the teeth (17). Wang et al. found a method based on the triangular mesh for the dental modeling and simulation. They used laser scanner to measure the teeth and the diametric shortest distance for triangular mesh generation (1). In this study, a new method was used based on measuring the teeth curves by image processing. This method is based on the surface automatic mesh generation, and is a combination of the two methods of Voxel and mesh generation.

A comprehensive knowledge of the teeth leads to the more accurate virtual three-dimensional modeling. A database that contains geometry and properties of human teeth are needed for dentistry education and dental researchers. A three-dimensional model of dental teeth can improve dental research and specialized training (18,19) as well as develop simulation software of oral surgery, orthodontics, and endodontic implants (20,21). The aim of this study was to create a three-dimensional model of the virtual teeth, used in dental education and the finite element analysis for dental research.

Methods

In this study, a cross-sectional picture of a tooth for three-dimensional modeling was used. In CT-scanning (the first method), whenever the space between the cuts is less, the resulting model would be more accurate. To create a three-dimensional model of a tooth, another method, other than CT-scanning, was used. Using this method would help compare the accuracy of the two methods. In the second method, we cut the tooth from the top of the crown



Fig. 1. The Teeth Were Mounted to Examine the Cross-section of the Tooth Images

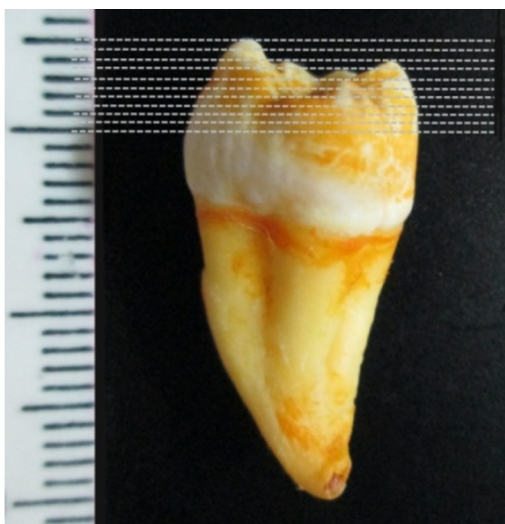


Fig. 2. Cutting Lines for Tooth Slices

to the root, with a space of 0.5 millimeters between the cuts. Then the cross-sectional

images of the tooth preparation were taken. The teeth were mounted to examine the cross-section of the tooth images as shown in Figure 1.

An example of the cutting lines on the crown of the maxillary third molar is shown in Figure 2. Pictures, taken in each level, were used in the teeth simulation.

In the first step, CT-Scan images were used, with a CT-Scan device (GE HiSPEED NX / I Pro CT) of the space of 50 microns between the sections. Time measured for each frame was about 20 seconds. For a tooth measurement, an average time of an hour was spent. On average, 80 images of each tooth were prepared. The space between the cross-sectional images was about 200 to 500 micrometers. In the next step, the hard tissue margin was detected in each image. Matlab (R2009b) was used as an image processing software.

The detection algorithm was based on the difference of color in the images, and ultimately this software defined the boundaries of the hard tissue. The boundaries were specified in the Matlab (R2009b) for each image. An example of image processing for the second premolar is shown in Figure 3.

The images were transferred to Solidworks 2015 software. Tooth border curve was fitted on B-spline curves, using least square-curve fitting algorithm with less than 5% error. An example of the fitted

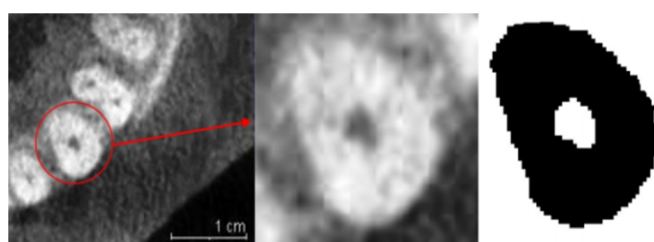


Fig. 3. An Example of the Detection of the Tooth Margin in Matlab

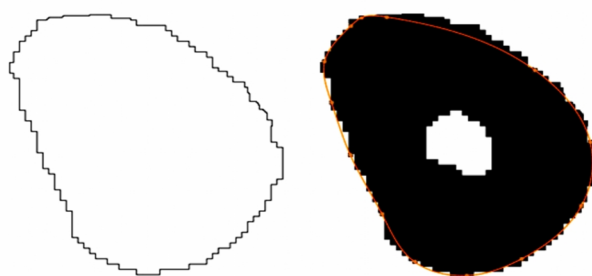


Fig. 4. An Example of Marginal Detection in Matlab and Its Adaptation on B-Spline Curve in Solidworks

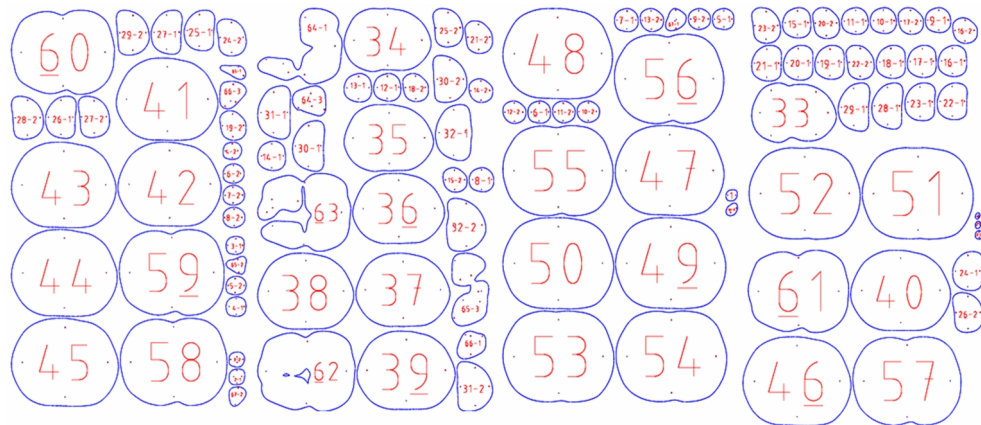


Fig. 5. A Set of B-spline Curves Used for Molar Teeth Modeling in Solidworks 2015

boundary lines is shown in Figure 4 (the red line is the example of curve fitting on the tooth border in Solidworks 2015 software).

To create boundary curves tooth, a cross-sectional image of each tooth was prepared with the space of 0.2mm from each other. The curves were transferred to Solidworks 2015 in compliance with the order. A series of images produced by this method are shown in Figure 5 (mandibular molars).

After transferring all curves to Solidworks for each tooth, the surface was created based on the surface fitting technique. This surface was meshed in Meshlab-v132 software, and the optimization of the surface was done based on the remeshing technique. Remeshing technique was based on the downsizing of the model meshes, and the pyramid tetrahedral mesh was used. An example of this method and creation of the model is shown in Figure 6. Initial model is shown in part A. Part D in Figure 6 displays the model after the remeshing technique. All apparent faults in this model have been corrected.

To assign the mechanical properties, we had to create an intrinsic structure of the tooth other than its surface. Cutting the section of intrinsic structure of the tooth is shown in Figure 7. Finally, the models were created with the format of "STEP".

To perform the finite element analysis on the model, the mechanical properties of the teeth should be allocated. The Young's modulus of tooth enamel ($E=88\text{GPa}$) was

attributed (22,23). The three-dimensional modeling algorithm used in the study is shown in Figure 8.

Rendering is the final step of the simulations that provides the model with real effects. The virtual three-dimensional model, which was created with real teeth, was used for comparison (Fig. 9).

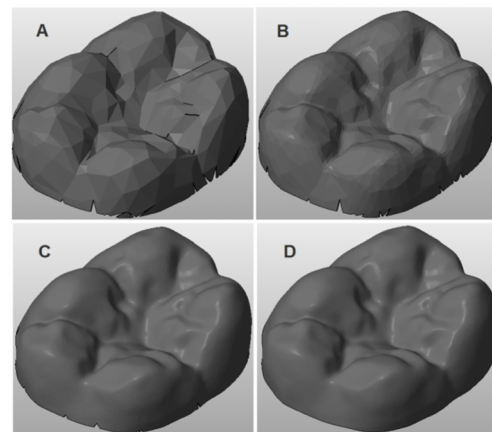


Fig. 6. Steps to Prepare and Improve the Quality of the Model Surface (A to D)

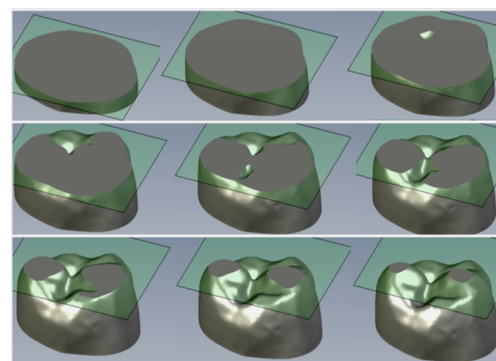


Fig. 7. Cutting the Section Images of the Tooth in

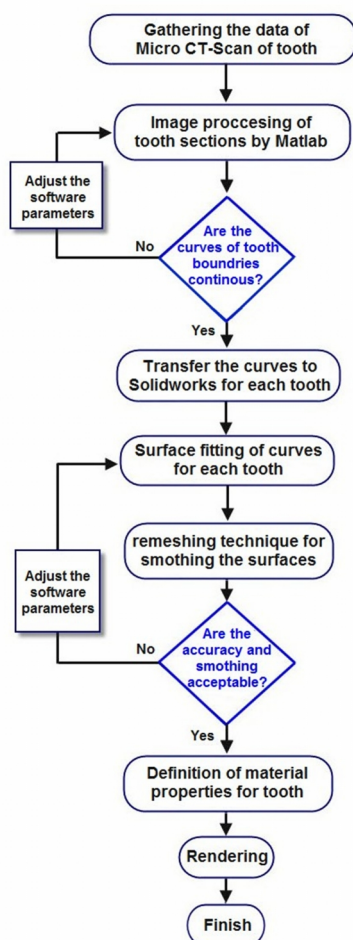


Fig. 8. The Three-Dimensional Algorithm Modeling of Teeth Simulation

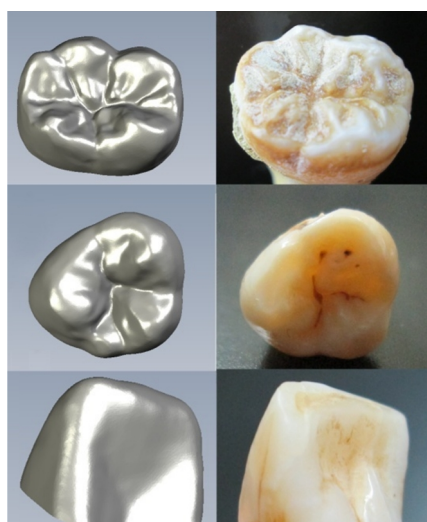


Fig. 9. Comparison of the Virtual Three-Dimensional Model of the Teeth with Real Teeth

Results

In this study, the cross-sectional images were used for modeling. In this model, the

cost and time were reduced compared to other studies. This modeling can be performed without destroying the structure of real teeth, and could be used in the finite element analysis for designing implants, dental prosthesis. To our knowledge, there was no reported document on the educational function of the finite element analysis in the literature. Without precise geometric dimensions of the teeth, the finite element analysis and E-learning will not be accurate. This study presented a methodology for communication between CT-scan images and the finite element and training software through which modeling and simulation teeth were performed.

Measuring the tooth dimensions demonstrate that the error was in the range of 5%. It is possible to obtain detailed models with high accuracy and less error, but this greatly increases the time and cost of modeling. The method described in this study has some advantages to the laser scanning method. One of the problems in laser scanning method is the lack of adequate access and lack of sufficient precision in the model.

Discussion

The three-dimensional models of the human body anatomy could improve medical education, describe a variety of diseases, and help determine the types of injury. In this study, by using images obtained from CT-scanning and the cutting sections of the teeth, three-dimensional models of teeth were created, whereas in other studies cloud points were used to create the three-dimensional model of teeth (23,24). In this study, the possibility of creating a virtual three-dimensional model of hard tissue (teeth) was provided. This model increases the quality of specialized training in dentistry and significantly improves the quality and accuracy of dental procedures.

Conclusion

The method presented in this study has the following basic characteristics:

- The three-dimensional model was more useful to the dental students and dentists.
- The method presented in this study, in comparison with the other methods, is more accurate and less expensive, and the possibility of creating a three-dimensional model of the tooth with respect to CT-Scan images is higher.
- Based on the three-dimensional model proposed, analysis of the design and manufacturing of implants and dental prosthesis are possible.
- It is possible to create a detailed model with maximum error of 50 micrometers by this model.

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