A Virtual System for Cavity Preparation in Endodontics

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Abstract: This article presents a novel virtual teeth drilling system designed to aid dentists, dental students, and researchers in getting acquainted with teeth anatomy, the handling of drilling instruments, and the challenges associated with drilling procedures during endodontic therapy. The system is designed to be used for educational and research purposes in dental schools. The application features a 3D face and oral cavity model constructed using anatomical data that can be adapted to the characteristics of a specific patient using either facial photographs or 3D data. Animation of the models is also feasible. Virtual drilling using a Phantom Desktop (Sensable Technologies Inc., Woburn, MA) force feedback haptic device is performed within the oral cavity on 3D volumetric and surface models of teeth, obtained from serial cross sections of natural teeth. Final results and intermediate steps of the drilling procedure can be saved on a file for future use. The application has the potential to be a very promising educational and research tool that allows the user to practice virtual teeth drilling for endodontic cavity preparation or other related procedures on high-detail teeth models placed within an adaptable and animated 3D face and oral cavity model.

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The success of endodontic therapy depends upon many factors, one of which is appropriate pulp cavity access. Therefore, familiarization with the technique of dental drilling for cavity preparation is an important part of a dentist's training that can aid him or her to learn how to achieve correct access of the root canals' system during endodontic therapy. Usually, dental students are trained on artificial teeth and jaws—sometimes placed within a manikin head—using real dental instruments and burs before they perform this procedure on patients.

A number of early studies that deal with the use of virtual reality technology in orthodontics,[1,2] restorative dentistry,[3] orthognathic surgery,[4] implantology,[5,6] and endodontics[7] can be found in the literature. All of these studies reported encouraging results. More advanced virtual reality-based cavity preparation training systems such as the DentSim system (DenX Corp., Jerusalem, Israel)[8] and others[9,10] have been introduced lately.

The goal of the dental drilling simulator described in this article is to provide a 3D model of the maxillofacial region, the oral cavity, and the teeth so that undergraduate or postgraduate dentistry students and researchers can get acquainted with the anatomy of the maxillofacial region and develop their dental drilling skills. Control of the dental burs is performed through the use of a force feedback haptic device that can simulate forces exerted on the bur during the procedure.

This article is organized as follows. The construction of the face/oral cavity model is described first, followed by a description of the procedure used to achieve model adaptation/personification and animation. Subsequently, the virtual teeth drilling procedure is presented. A discussion including some preliminary results from a small-scale pilot study that involved a small number of students follows.

Anatomical Face/Oral Cavity Modeling

In order to create a realistic three-dimensional face/oral cavity model, a number of anatomically meaningful 3D points were recorded on the various head tissues by using manual modeling techniques.[11] The publicly available anatomical cryosections and CT (Computer Tomography) data of a male cadaver originating from the Visible Human Project (National Institutes of Health, USA)[12,13] were used for this purpose. Using this procedure, a 3D surface model consisting of 1,392 3D points and 2,209 triangles distributed among eleven different anatomical entities was created. The model includes the external face area, lips, cheeks, palate, tongue, gums and teeth, larynx, and uvula. Each of these structures is represented as a triangular mesh (Figure 1).

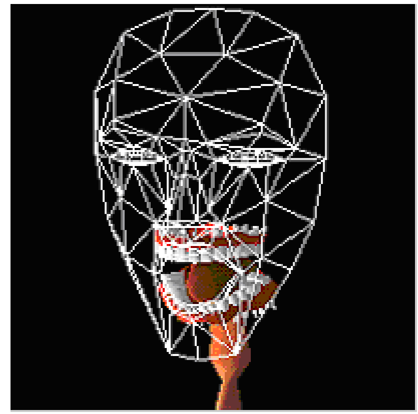

Figure 1. The face/oral cavity 3D model utilized in the virtual teeth drilling application

Note: The model includes the external face area, lips, cheeks, palate, tongue, gums and teeth, larynx, and uvula, represented as triangular meshes.

Model Adaptation/Personification

Within the developed simulator, the user can adapt the generic oral and maxillofacial 3D model to the characteristics of an individual person. A semi-automatic approach that relies on two photographs of the person, taken from two perpendicular directions (frontal and side), was used for this purpose (Figure 2). The adaptation is supported by a 2D FEM (Finite Element Model). This approach was selected because it offers speed and reliability in the adaptation procedure and requires only a small amount of interaction with the user.

The approach uses a two-step adaptation process. In the first step, the user performs global translation and scaling on the facial model that is overlaid on the two photographs. The models of the anatomical structures within the oral cavity (jaw, gums, etc.) are scaled and translated automatically in the same way as the facial model. To proceed with a detailed adaptation of the 3D model on the photographs, user interaction along with a 2D Finite Element Method (FEM)[14] that is capable of being deformed in real time is used in the second step. Essentially, the model's 3D-mesh is represented as a system of springs that can be deformed through user interaction. To perform the adaptation, the user uses the mouse to move a certain number of vertices of the model's mesh to the corresponding points in the picture. For example, the user moves with the mouse the point of the 3D mesh that corresponds to the tip of the nose and places it over the tip of the nose of the person depicted in the photograph. Subsequently, the FEM moves the remaining vertices of the mesh, i.e., those that have not been displaced by the user. This operation is executed in real time so that the user can see the results of the interactive adaptation.

The FEM-based user-guided adaptation is applied only on the facial model. During this adaptation, the models of the oral cavity anatomical structures (palate, tongue, gums and teeth, etc.) are translated and scaled according to the position and scale of the model's mouth and the width of the jaws.

As a final stage of the model adaptation/personification, the user can select through a graphic representation of the teeth the ones that he or she wishes to remove from the model (Figure 3). This is useful if one wishes to create models of patients that lack some of their teeth. The user can also control which parts of the model (face, gums, tongue, etc.) will be visible.

In addition, the user can replace (within the 3D oral cavity model) the limited resolution prototype of a certain tooth where virtual drilling will be performed with a more detailed model. For this operation, the user provides the volumetric (voxel-based) model of the tooth. This model is constructed from the digital images of serial cross sections where the structures of interest (external tooth surface and root canals) have been segmented. A database of such volumetric models for all teeth categories (incisors, canines, premolars, and molars) is provided along with the application. This database has been constructed by digitizing and post-processing (alignment and segmentation) physical cross sections of extracted teeth, viewed through a stereoscopic microscope.

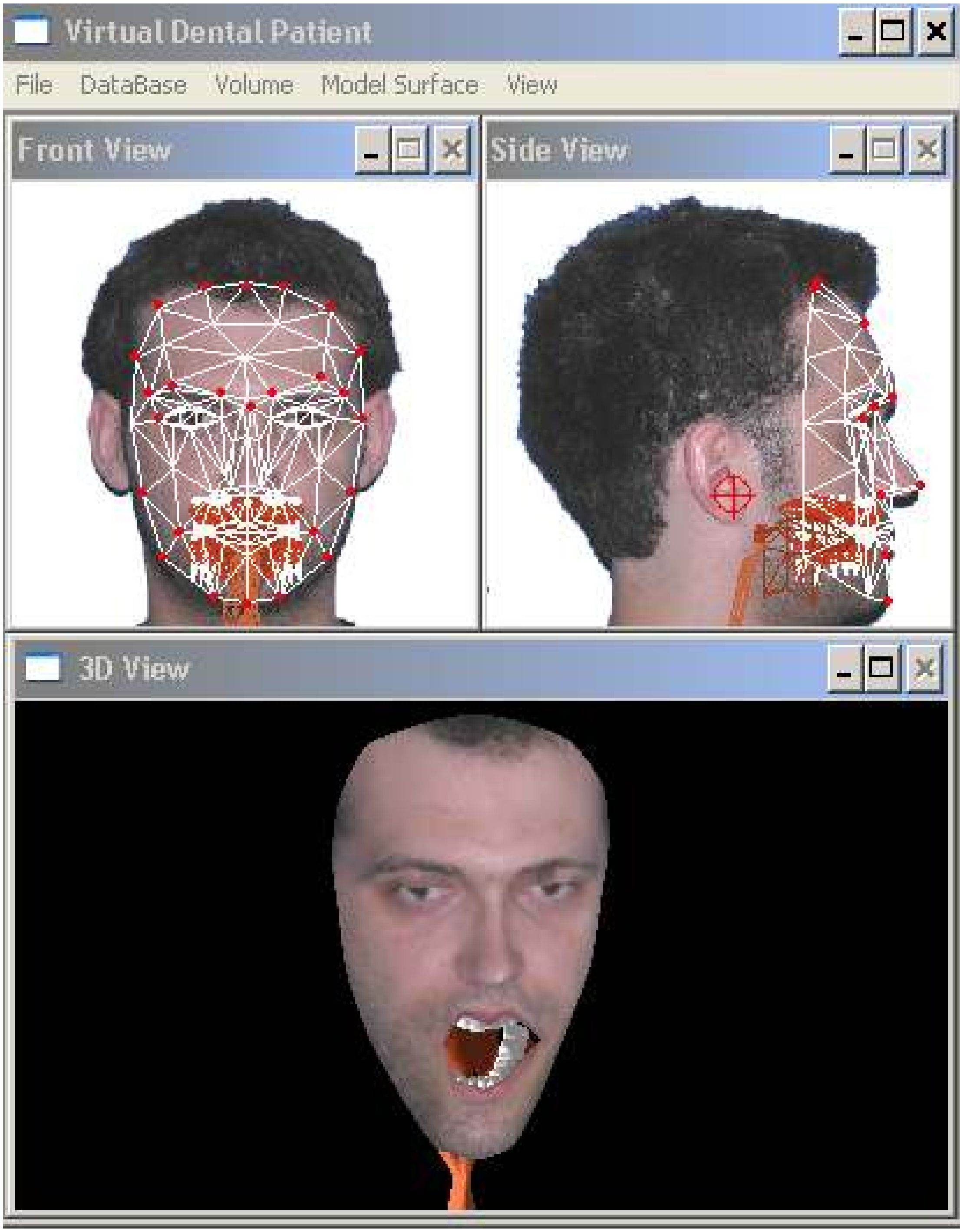

Figure 2. Model adaptation-personification using two facial photographs

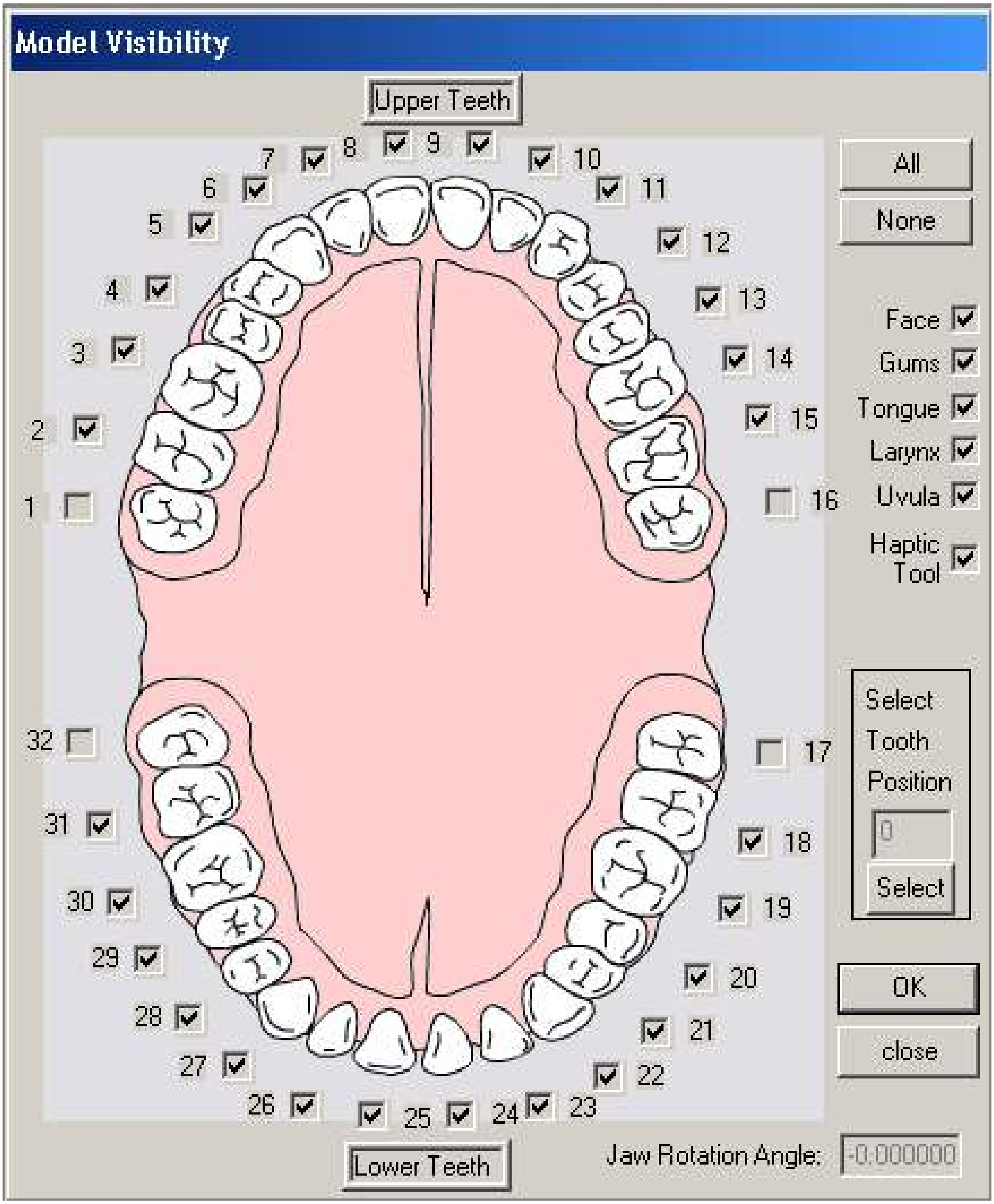

Figure 3. Selection through a GUI of the teeth of the virtual patient that will be displayed

The application loads the volumetric (voxel-based) representation of the tooth (required for the drilling procedure as will be explained later) and also applies the Discrete Marching Cubes algorithm[15] to obtain the surface representation of the tooth and embed it in the face/oral cavity model. The selected tooth is inserted into the face/oral cavity model in two steps: 1) coarse automatic placement of the tooth on the gums by using information about the size of the teeth models and the alveolus; and 2) optional manual adjustment, i.e., rotation, translation, and scaling. After the adaptation, texture mapping (use of the two facial images in order to add texture/color information to the 3D face model) can be applied to achieve additional realism.

Model Animation

For animating the models, compatibility with the facial animation part of the well-known MPEG-4 standard is provided. More specifically, the application includes an FAP (Face Animation Parameters) player that reads FAP files (files that describe the movement of certain points of the 3D model) from disk and animates the model (Figure 4). For example, a file that instructs the model to open its mouth and protract its tongue can be applied. The user can save the model configuration at a certain frame of the animation in the well-known Virtual Reality Modelling Language (VRML) format.

Since the MPEG-4 facial animation standard handles only movements of the face, the movements of the intraoral anatomical structures that are not covered by the standard should be also defined. More specifically, the movement of the lower jaw (along with the lower teeth, gums, and tongue) is defined as a rotation around a user-specified axis. This rotation is controlled by the chin movement. A similar procedure is used to control the lower jaw horizontal translation (along with the influenced structures, namely, the lower teeth, gums, and tongue).

During the animation, real-time surface subdivision using the Point-Normal triangles technique[16] (generation of a 3D model with more triangles) is used in order to improve the visual quality of the models and obtain smooth surfaces.

Virtual Tooth Drilling

When loading of a high-detail tooth model is finished, the user can proceed to perform virtual drilling on this tooth. For this purpose, both the volumetric and the surface representations of the tooth are available to the application. The reason for this is that, in the proposed approach, removal of material during drilling is implemented as a series of morphological operations (erosions) on the volumetric (voxel-based) representation of the object, involving 3D structuring elements that represent the shape of drilling tools (dental burs).[17] This approach can be

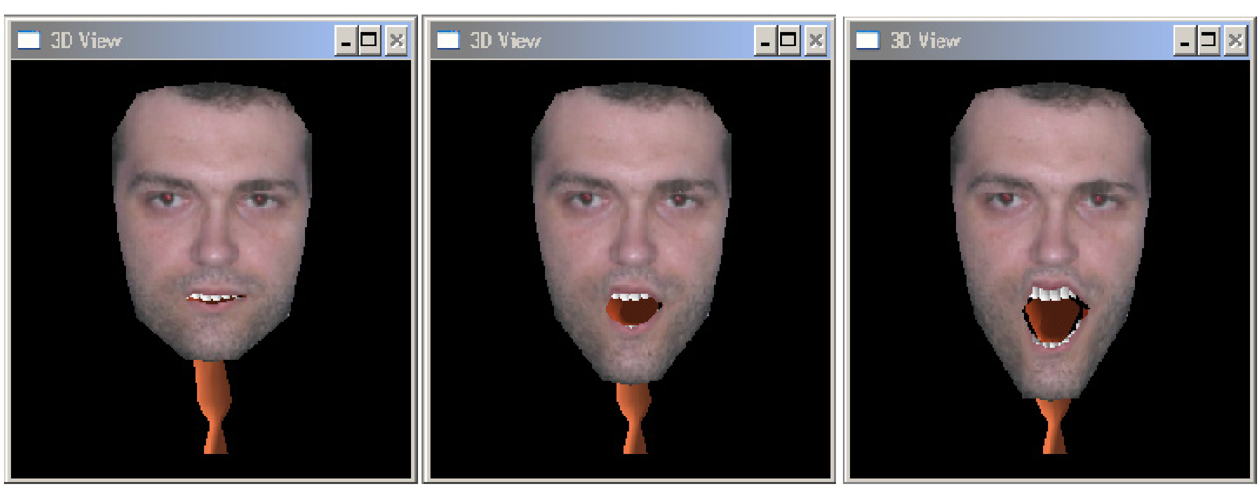

Figure 4. Animation frames extracted from an MPEG-4 video file

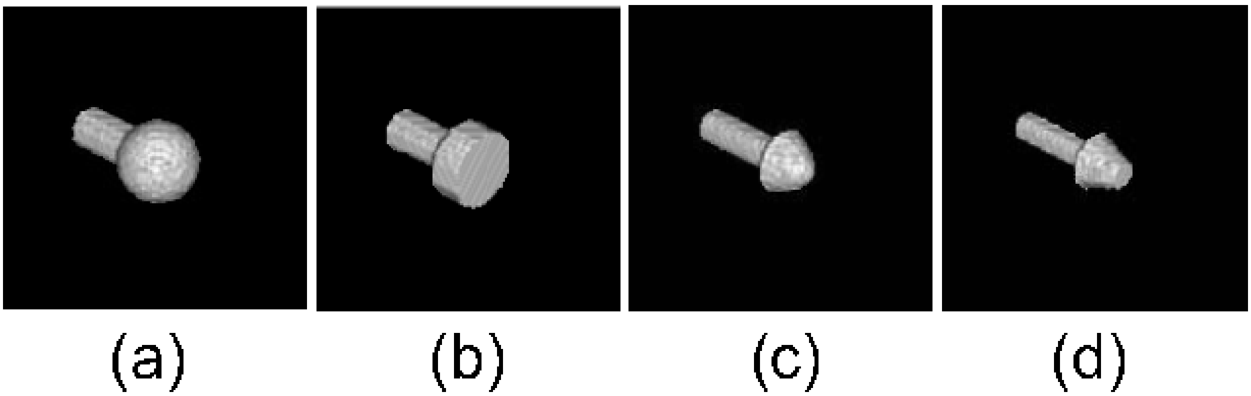

Figure 5. Four types of virtual burs of different sizes: spherical bur (a), cylindrical bur (b), conical bur (c), and cylinder-conical bur (d)

used to implement almost any kind of drilling tool shape. Four basic dental bur shapes—a spherical, a cylindrical, a cylindrical-conical, and a conical (which is a special modification of the cylindrical-conical one)—have been employed (Figure 5). The user can select the appropriate drilling tool and define its shape parameters (e.g., the radius for the spherical tool). The parameters of a virtual drilling tool can be saved for future use. Moreover, a database of virtual dental burs whose shapes and dimensions match those of commercially available ones has been created and accompanies the application.

At this stage, the user can perform (if needed) the following two operations on the volumetric tooth model: 1) add material on the surface of the volume; this is implemented by using 3D dilations; 2) smooth the surface of the volume locally by using the mouse and by selecting an appropriate smoothing window.

The dental drilling operation can be performed directly on the stand-alone volumetric model of the tooth using the mouse. However, more realism can be achieved by performing drilling on the surface model of a tooth that has been inserted within the full oral and maxillofacial 3D model. Either the mouse or a haptic device can be used to control the operation (Figure 6). The Phantom Desktop six degrees of freedom positional sensing force feedback haptic device has been used for this purpose.

Using the haptic device, the user can perform dental drilling while sensing contact/resistance forces. The force value is determined by the properties (stiffness, static, and dynamic friction) of the object, as set by the user.[18] The stylus of the haptic device controls the position of the virtual dental bur, which is also visible in the scene (Figure 6).

During the material removal operation, the application uses the internal dual surface/volumetric representation of the tooth. This dual representation is necessary since the GHOST SDK (Sensable Technologies Inc., Woburn, MA)[19] that is used for handling the tool-tooth physical interaction requires that the object is represented by its surface, whereas the proposed mathematical morphology-based material removal algorithm operates on the volumetric representation of the tooth.

Users can select to track the performed drilling operations, i.e., to keep a “history” of the performed operations. If users choose to keep track of these operations, they can undo a certain number of them. Furthermore, they can save the sequence of operations on a file and reapply them on the tooth in the future.

The tooth that has been subject to a dental drilling operation can be saved either in volumetric form (as a series of cross sections) or as a surface representation (as a triangular mesh). The supported mesh formats are Virtual Reality Modelling Language (VRML), Drawing Exchange Format (DXF), and StereoLithography (STL). The latter is a format used in stereo-lithography and can be fed to a stereo-lithography device to construct a real 3D model of the tooth out of the virtual model. An example of a virtual tooth that has been drilled with the developed application can be seen in Figure 7. During drilling, the user can enable stereo viewing through active

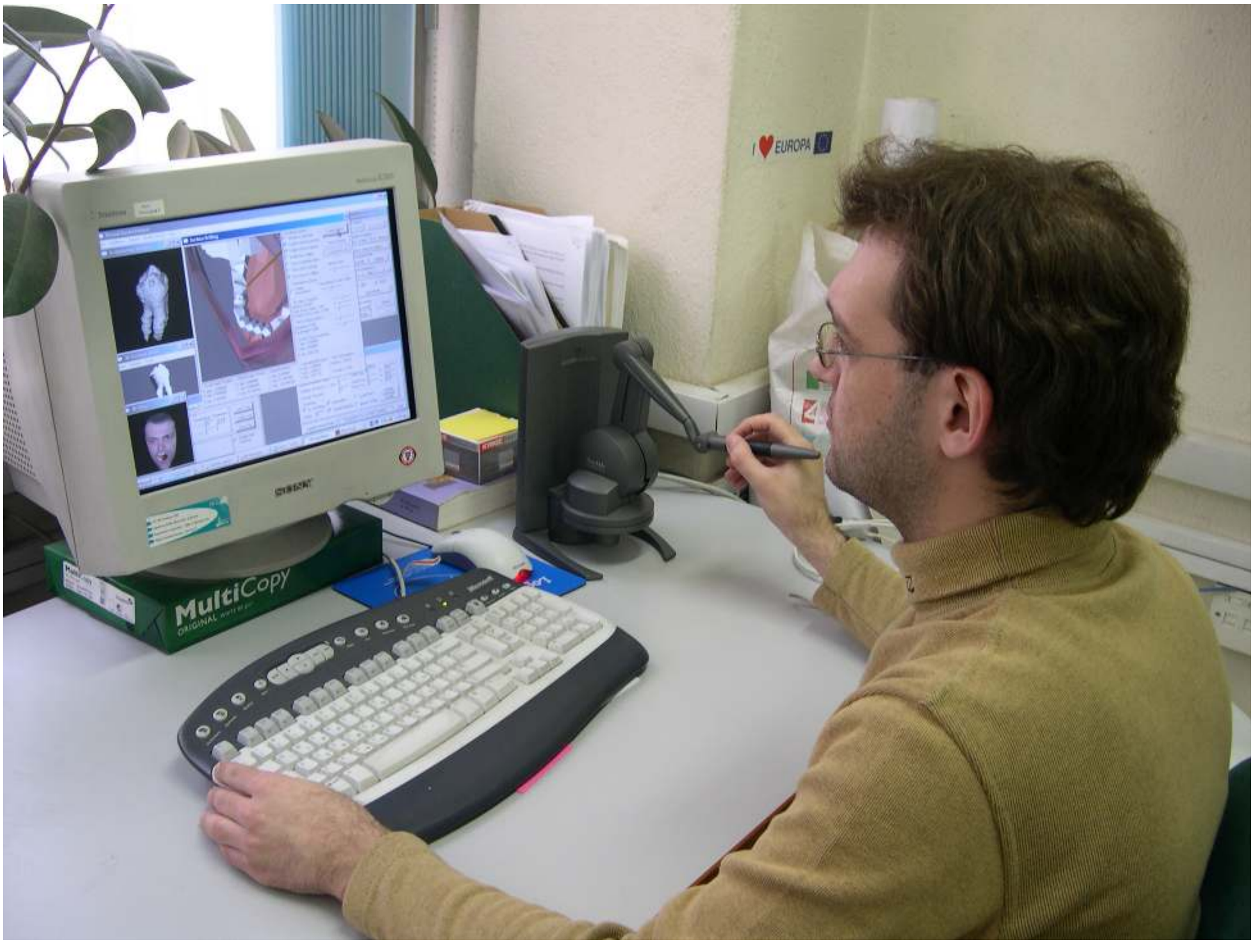

Figure 6. Using the phantom desktop haptic device with the virtual teeth drilling application

shutter glasses and get a sense of depth in the scene. In addition, the application provides transparency options that allow the user to visualize certain parts of the model as semi-transparent (Figure 7c). This is a very useful option that enables the user to observe the anatomy of the root canal system during the virtual preparation of the endodontic cavity.

Discussion

Some virtual reality-based cavity preparation training systems have been recently introduced in the field of dental education and research. The DentSim system (DenX Corp., Jerusalem, Israel)[8] is comprised of a real dental unit, a manikin head, a tracking system, and software that allow the student to view the results of his or her cavity preparation in the manikin head on 3D models presented on a computer monitor and compare them with the results of an optimal preparation. Other systems[9,10] involve a 3D virtual tooth and a Phantom haptic device (Sensable Technologies Inc., Woburn, MA)[19] that enable the trainee to perform virtual drilling while receiving appropriate force feedback. The systems described in both these articles operate on stand-alone teeth, and the focus is on providing realistic material removal simulation as well as realistic force rendering. However, such a simulation would be much more realistic if cavity preparation were performed on teeth placed within the oral cavity.

Such an option is provided by the novel virtual tooth drilling simulator that has been described here. This simulator allows the user to view/manipulate a

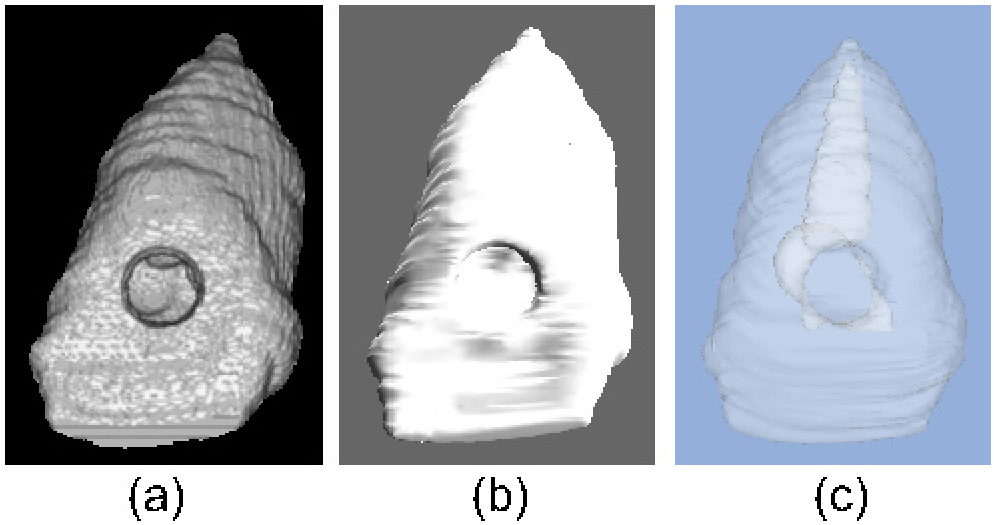

Figure 7. Volumetric (a) and surface (b) representation of an upper central incisor that has been drilled with the developed application; the semi-transparent model (c) of the same tooth that allows visualization of its root canal

3D face and oral cavity model constructed using anatomical data, adapt the model to the characteristics of an individual patient using either facial photographs or 3D data, animate it using an MPEG-compatible facial animation player, and perform virtual tooth drilling within the oral cavity. A Phantom haptic device can be used to control the drilling tool while providing force feedback during the drilling operation and thus increasing the level of realism. Drilling is performed on 3D volumetric/surface models of teeth, obtained from serial cross sections of natural teeth.

Apart from being used as a training tool for students, the system can also assist experienced dentists in planning a clinical teeth drilling intervention by getting familiar with the individual patient anatomy, identifying landmarks, planning the approach, and deciding upon the ideal target position of the actual clinical activity. Small-scale usability tests involving fifteen dental students and researchers and a professional dentist were recently performed. The students were given the opportunity to use the application to perform some simple cavity preparation tasks and then were asked to comment anonymously on its usefulness. The responses showed that the users believe that the system constitutes an interesting and useful package for dental drilling simulation, which simulates all the important procedures a dentist has to undergo to gain experience.

In conclusion, the dental simulator described here has the potential of being a very promising educational and research tool that allows the user to practice virtual tooth drilling for endodontic cavity preparation or other related procedures on high-detail teeth models placed within an adaptable and animated 3D face and oral cavity model. Furthermore, the user can save the sequence of the drilling operations on a file and reapply them. Thus, if inexperienced users make an error during the procedure of the virtual drilling, they can undo their last drilling steps and continue to the right direction. Moreover, an instructor can view the drilling procedure as performed by a trainee and judge its skill level.

So far, our work has focused on developing the visual part of the application. Future work will focus on developing realistic and physically accurate material removal and force models that will take into account all the involved factors. More extensive usability tests and pilot studies are also under way. These studies will involve a larger number of students, longer periods of interaction with the system, and a more detailed questionnaire that will call for the student's opinion on a number of issues (ergonomics/usability, realism, etc.). The studies will also involve a comparison of cavity preparation skills acquired through the use of the proposed system with those obtained when traditional practice methods are used.

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