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Haptics-based virtual reality periodontal training simulator

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Abstract This paper focuses upon the research and development of a prototype dental simulator for training of periodontal procedures. By the use of virtual reality and haptics technology, the periodontal simulator allows trainees to learn performing diagnosis and treatment of periodontal diseases by visualizing a three-dimensional virtual human mouth and feeling real tactile sensations while touching the surface of teeth, gingiva, and calculi with virtual dental instruments. Since periodontics requires dentists to depend primarily on tactile sensations to perform diagnostic and surgical procedures, the use of haptics is unquestionably crucial for a realistic periodontal simulator. The haptics-based virtual reality periodontal training simulator has been validated by a experiment conducted by the College of Dentistry at University of Illinois at Chicago (UIC) with faculty members and dental students, which demonstrates the scientific contribution and usefulness of the simulator as a vital part of the curriculum of the Department of Periodontics at UIC.

Keywords Virtual reality · Simulation · Training · Haptics · Dentistry · Periodontics

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1 Introduction

The use of medical simulators has proved to increase patient safety and reduce risk associated with human errors in hospitals by allowing medical students to develop skills more efficiently in a shorter period of time. Even though medical simulators are currently being developed by a large number of universities and medical companies, the field of dental simulation has not been well exploited yet. This article focuses on the research and development of a haptics-based dental simulator specially designed for training and performance evaluation of dental and hygiene students and practicing professionals in periodontics. The simulator is the result of a multidisciplinary project developed by the *Electronic Visualization Laboratory* of the Department of Computer Science, the *Industrial Virtual Reality Institute* of the Department of Mechanical and Industrial Engineering, and the Department of Periodontics at the University of Illinois at Chicago (UIC). The goal of this collaboration between the College of Engineering and the College of Dentistry at UIC is the implementation of a dental simulator to help increase the quality of training for students and future practitioners in the field of periodontics. The simulator allows trainees to develop the skills needed to differentiate pathological and normal conditions, as well as to diagnose and treat periodontal diseases. Trainees can learn by feeling tactile sensations as they "touch" a computer-generated 3 dimensional (3D) model of a human upper and lower dental arches along with various oral components: teeth (crown and roots) and gingiva with a haptic device. The simulator also facilitates the learning of proper selection and manipulation of dental instruments to perform periodontal procedures.

This article is organized in six sections. Section 2 presents an overview of the current commercially-available medical simulators, followed by manikin-based and haptics-based dental simulators previously developed. Section 3 gives background information about the diagnosis and treatment of most common periodontal diseases and proposes the use of haptics-based dental simulators to facilitate the learning of these activities. Section 4 shows the implementation details and the graphical user interface of the virtual reality periodontal simulator. Section 5 describes the use of the simulator for periodontal training, and reports the results obtained after its evaluation by the College of Dentistry at UIC. Finally, Sect. 6 outlines the conclusions of this work and suggests future research and development.

2 Background

In the last decade, medical simulation has become a valuable learning and practicing tool for acquiring skills that were, until recently, performed by practice on laboratory animals, cadavers and even on living humans. Animals do not have the same anatomy as human beings, are expensive, and they are not reusable. Cadavers have the correct anatomy, but they are expensive, difficult to procure, and present some tissue degradation problems. On top of that, ethical issues are raised in both cases.

Simulation-based medical training provides an enhanced clinical skill development that benefits, not only patients but also health care consumers. According to (IOM 1999) from 44,000 to 98,000 patients die each year as a result of “medical errors”, causing an estimated cost to the US economy of $17–$29 billion dollars. Medical simulation improves health outcomes, patient safety and quality, reduces medical errors and deaths, and increases healthcare cost savings.

Common medical procedures, such as laparoscopy, colonoscopy, lung biopsy, vascular access and cardiovascular catheterizations, can be performed on physical manikins and computer-based simulators to train medical professionals without putting real patients in risky situations (Immersion Medical, http://www.immersion.com/medical/). Previous studies (Rowe and Cohen 2000; Mehta et al. 2000; Datta et al. 2001; Wong et al. 2001) indicates that training on simulators has significantly improved students’ skill and performance on patients when compared to those individuals not trained on these devices.

Previous work on dental simulation focused more on mouth movement analysis rather than on education and procedural training. Computed Tomography (CT) and computer animation techniques were successfully used in dentistry to analyze the mandibular movements of patients (Enciso et al. 2003a, b; Shigeta et al. 2003), and to create a 4D mathematical model to identify the muscle contractions of patients with certain anatomical characteristics (as square mandible) (Shigeta et al. 2005). Thin-plate splines were used to model the 3D geometry of a tooth to match 2D patient radiographs, without the need for CT images (Enciso et al. 2003a, b).

Even though complex and realistic medical simulators are becoming more and more common in medical education, the use of simulators in the field of dentistry has not been well exploited yet. Dental simulators provide an efficient way to quickly teach preclinical dental students on dental procedures while increasing their hand skills considerably. Repetitive procedures such as proper hand and instrument usage and placement are primary targets to be learned on dental simulators.

There are two kinds of dental simulators currently available: manikin-based simulators that provide a physical model of the patient’s head and mouth on which certain dental procedures can be performed using real dental instruments; and haptics-based simulators that employ a PHANToM™ haptic device [SensAble Technologies, Inc, http://www.sensable.com] and virtual models of a human tooth or mouth as a platform to facilitate dental practicing. Instead of using real dental instruments, the trainee holds the haptic device stylus to manipulate a set of virtual instruments that are shown on a monitor screen. The tactile feedback reproduces clinical sensations in the hand of the operator using dental instruments.

2.1 Manikin-based dental simulators

There are two companies that commercialize similar manikin-based dental simulators worldwide: DenX and KaVo.

- DentSim™, developed by DenX Ltd (http://www.denx.com) consists of a manikin with head and dentoform (plastic teeth), a dental hand-piece and a light, an infrared camera and two computers. The manikin head and the hand-piece contain infrared emitters that are tracked by the infrared camera. Using this optical tracking system to trace the movements of a hand piece, the simulator scores the accuracy of a student’s cavity preparation in a manikin’s synthetic tooth.
- Image guided implantology (IGI), also developed by DenX, Ltd, uses the same technology of DentSim™ for teaching, diagnosis, treatment planning and placement of implants. Providing a particular patient’s CAT scan, the simulator allows the patient and the virtual model image to be coordinated during the actual surgery. If the computer recognizes that the surgeon is making a serious deviation from the treatment plan during the actual surgery, the computer will stop the hand-piece and the surgeon will need to override the computer to continue.

- Dental simulation unit plus (DSEplus), commercialized by KaVo (http://www.kavousa.com/products/dental_education/dse/dse.asp?navid=5200&lan=Us) is a complete training unit with pneumatic chassis, storage space, supply unit, pressurized water module, suction module, dentist's element with instrument tubes and 3-F syinge, assistant's element with two suction tubes, foot control, patient simulator, cranium with jaws, tooth model, face mask and pneumatic patient positioning system.

The use of manikin-based dental simulators, compared to the traditional preclinical methods, increases the educational outcomes according to (Buchanan 2001, 2004). Jasinevicius et al. (2004) found that even the instruction time spent by faculty is decreased when using DentSim™ simulators. In addition, a higher number of students can be trained on technical skills at the same time, because the traditional time-consuming one-to-one relationship between the student and the instructor is not required any more (Chan et al. 2000).

However, those simulators present the following disadvantages:

- A physical model or manikin needs to be frequently replaced, increasing the maintenance costs considerably.
- They do not provide any indications if the treatment performed by the student would be potentially aggressive for a real patient.

In order to overcome these two problems, (Sae-Kee 2003) developed a dental training simulator mounting a bigger-than-real plastic model of a single tooth on a 6-DOF sensor connected to a computer. The trainee interacts with the simulator by actually touching the physical tooth model. The sensor is able to measure force and torque applied to the physical model while a monitor displays a virtual version of the tooth model. That system presents severe inconsistency problems caused by the fact that there is no actual drilling on the physical model while the shape of the virtual model changes as the drilling simulation evolves. Therefore, the position and orientation of the virtual burr instrument touching the virtual model become inconsistent with the real ones, limiting the usefulness of the simulator (Sae-Kee et al. 2004).

An early attempt to incorporate haptics in simulation of teeth cleaning was achieved by (Gockel et al. 2002). The simulator offers guidance for optimizing the design and manufacturing of new toothbrushes by rendering the deformation of a virtual toothbrush as it makes contact with the virtual teeth. The system uses volumetric prototypes (like spheres and cylinders) to represent the surface model. Even though the original thought was to incorporate haptics to manipulate the virtual toothbrush, the authors reported that the volume-based multi-point collision detection developed by them was not fast enough to allow haptic interaction; hence a keyboard was used to move the toothbrush in 6 DOF.

2.2 Haptics-based dental simulators

Unlike manikin-based, haptics-based simulators are much more cost effective because no physical models need to be replaced. In addition, since the haptic device measures the forces applied by the trainee when touching the virtual patient's mouth, it is possible to detect when the trainee's action is too aggressive.

The followings are some of the most well-known haptics-based dental simulators previously developed:

- Virtual reality dental training system (VRDTS) was developed by Novint Technologies (http://www.novint.com/VRDTS.htm6) in collaboration with the Harvard School of Dental Medicine. Aiming for cavity preparation, the software simulates a set of dental instruments (low speed drill, an explorer, two carvers, a carrier and a packer), amalgam material, and a single molar including enamel, dentin, caries and pulp materials.
- Iowa dental surgical simulator (IDSS, http://grok.ecn.uiowa.edu/Projects/medsim.html) was a joint project between the College of Dentistry at the University of Iowa and the Graphical Representation of Knowledge (GROK) Lab. Participants can feel enamel, healthy dentin and carious dentin as touching the virtual tooth.
- 3DDental, commercialized by (SimuLife 2002), provided tactile feedback to reproduce clinical sensations (such as probing caries, drilling and filling of cavities) in the hand of the operator using a virtual explorer or a drill. 3DDental simulator is no longer available.
- A haptically-enabled dental simulator (Montgomery et al. 2005) combined tooth-specific micro-CT scans, microgrindings, and high-resolution photographic images to create a single virtual 3D tooth, on which the user was able to simulate the sensation of tooth preparations.
- A volume-based dental simulator (Kim and Park 2006) allowed dental student to learn procedures like dental probing, diagnose carious lesions, drilling operations for cavity preparations and filling the cavities with amalgam. The simulator used volumes for haptics rendering and polygonal meshes for graphics rendering.

Even though the previous haptics-based dental simulators have proven to be successful in the simulation of restorative dentistry such as caries preparation or filling of cavities, none of them focuses on the simulation of periodontal procedures. Unlike previous developments, this haptics-based dental simulator was designed especially for

Fig. 1 Periodontal probe

Fig. 2 Healthy tissues [Enexus][Hafernik]

periodontics.[1] This field of dentistry requires dentists to depend primarily on their tactile sensations, for both diagnostic and surgical procedures. This makes haptics ideally suited for periodontal simulators.

3 Periodontal procedures

3.1 Periodontal diseases

Periodontal diseases are bacterial gum infections that destroy the attachment fibers supporting bone that hold teeth in place. The main cause of periodontal diseases is bacterial plaque. If plaque is not removed, it can turn into a hard substance called calculus in less than 2 days. If calculus forms below the gum line, on the root of the tooth, it makes plaque removal more difficult, possibly causing a periodontal disease.

Toxins produced by the bacteria in plaque irritate the gingiva (gums), causing infection that can destroy the supporting tissues around the teeth, including the bone. When this happens, gums separate from the teeth, forming pockets that fill with even more plaque and more infection. As the disease progress, these pockets deepen, more gum tissue and bone are destroyed, and the teeth eventually become loose. If periodontal diseases are not treated, the teeth may need be removed [Racine Dental Group].

[1] A preliminary implementation of the UIC periodontal simulator, with a single tooth, was developed by (Montanari 2003) in an early stage of this project (Steinberg et al. 2003).

3.2 Diagnosis of a periodontal disease

Periodontitis is diagnosed by the use of a periodontal probe (Fig. 1), which is a depth measurement device. With very little pressure, the probe is slipped down next to the root of the tooth until there is a resistance. The markings shown on the instrument demonstrates the depth of the gum pocket (in millimeters).

The severity of the periodontal disease is measured according to the depth of the gum pocket. The following table shows a comparison of the possible cases of periodontitis and their related symptoms [Enexus, http://www.enexus.com/gumdisease/] [Hafernik, http://www.austindental.com/more/gum.shtml].

- *Healthy tissues*: No bleeding or puffy gums, all normal pockets measure 3 mm or less (Fig. 2).
- *Periodontitis I* (*Gingivitis*): Bleeding gums when measured, puffy in appearance and pockets no greater than 3 mm. No damage to the supporting bone in this stage (Fig. 3).
- *Periodontitis II:* Bleeding and puffy gums that measure slightly more than normal at up to 5 mm (Fig. 4).
- *Periodontitis III:* Bleeding and swollen gums with pockets that measure up to 6 mm and more. Bone recession beginning to appear. (Fig. 5).

3.3 Treatment of periodontal diseases

Treatment for all stages of a periodontal disease involves the thorough removal of all plaque and calculus that has

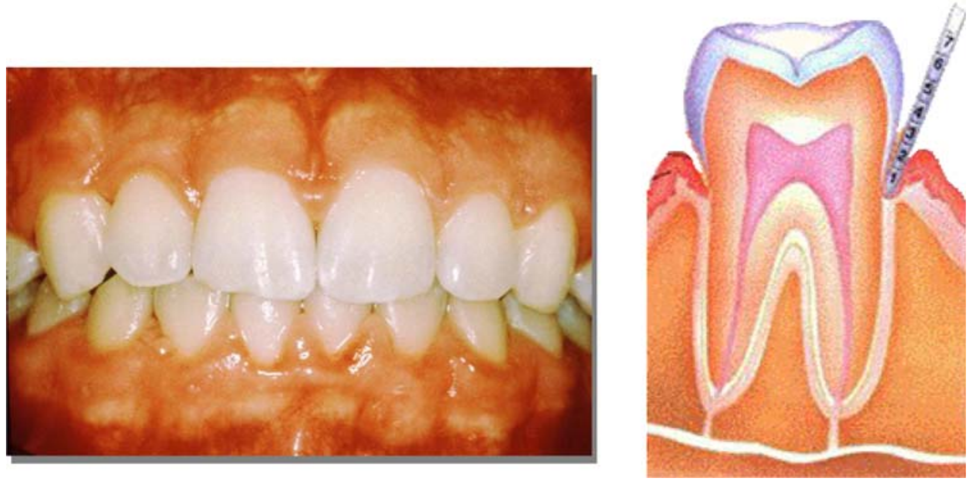


Fig. 3 Periodontitis I (Gingivitis) [Enexus][Hafernik]

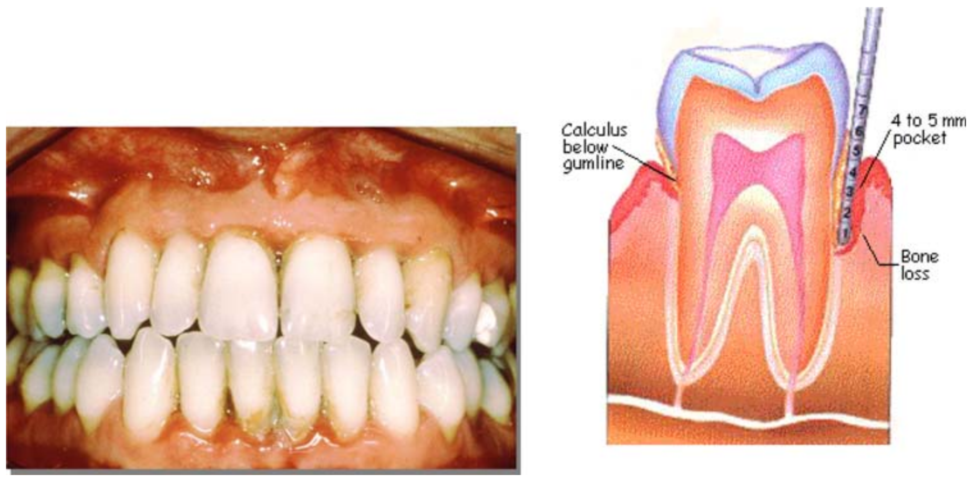


Fig. 4 Periodontitis II [Enexus][Hafernik]

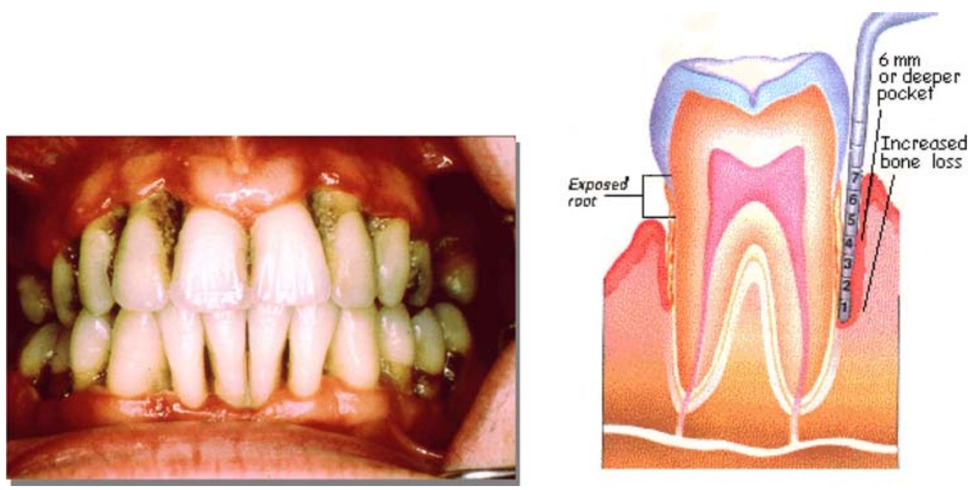


Fig. 5 Periodontitis III [Enexus][Hafernik]

adhered to the teeth. This can be removed during a normal prophylaxis without too much discomfort on the part of the patient. When the damage from gum disease is slight, this can be done without local anesthesia. The process is called "scaling" (Fig. 6).

When the damage from periodontal disease is more pronounced, exposing more root structure above bone, the process is called "root planning" (Fig. 7). Root planning always requires local anesthesia. The root of a tooth is naturally sensitive, and that is why local anesthesia may be

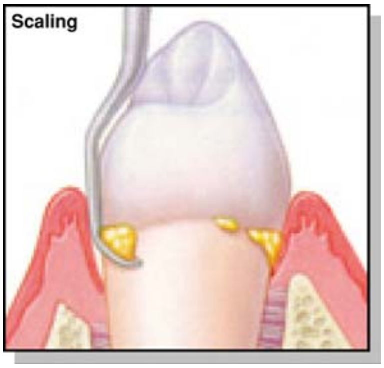


Fig. 6 Scaling [Peterson]

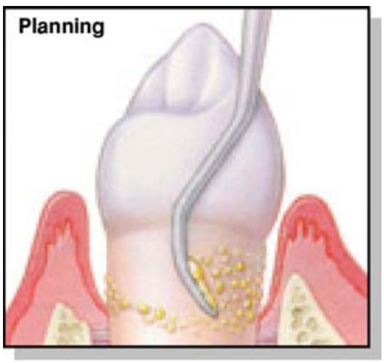


Fig. 7 Planning [Peterson]

needed when working in this area [Spiller, http://www.doctorspiller.com/Gum_Disease.htm, http://www.doctorspiller.com/Treatment_of_Perio.htm] [Peterson, http://www.dentalgentlecare.com/scaling__root_planning.htm].

Scaling and root planning are performed using a dental instrument called periodontal scaler (Fig. 8), which removes plaque and calculus from below the gum line. This controls the growth of destructive bacteria, and helps the gums to reattach to the root of the tooth.

As a final procedure, a periodontal explorer (Fig. 9) is used to determine by the sense of touch whether the scaled root surface has the calculus removed and has been properly instrumented. The periodontal explorer is also used to evaluate the area of the root surface covered by the gingiva to assess for the presence of dental caries on the root surface, assess abnormalities in root morphology and evaluate the presence of improperly finished dental restorative margins.

3.4 Learning periodontal procedures with haptics-based dental simulators

Currently in Dental Schools, periodontal procedures are taught by instructor demonstration, use of practice manikins and, finally, by actual work in the patient's mouth. This time consuming teaching process requires excessive one-on-one instructor/student interaction. Haptics-based dental simulators could facilitate the training of dental and hygiene students in these periodontal procedures. They should aid in diminishing the instruction time period, enhance the learning curve and provide for unlimited practice of these treatments.

In the diagnosis phase, a virtual periodontal probe could be used to measure pocket depth and determine the tissue health and, in case of pathological situations, the severity of the periodontitis.

In the treatment phase, a virtual periodontal scaler could be used to detect the presence of calculus. With the tooth surface covered by gingiva, the trainee would be forced to rely on the tactile sensation provided by the haptic device to evaluate the presence of virtual calculus on the root surface. Showing a transparent gingiva, the trainee could concomitantly see the calculus under the gum line.

In the evaluation phase, a virtual periodontal explorer may be used to determine that the calculus has been completely removed. This evaluation could be performed

Fig. 8 Periodontal scaler

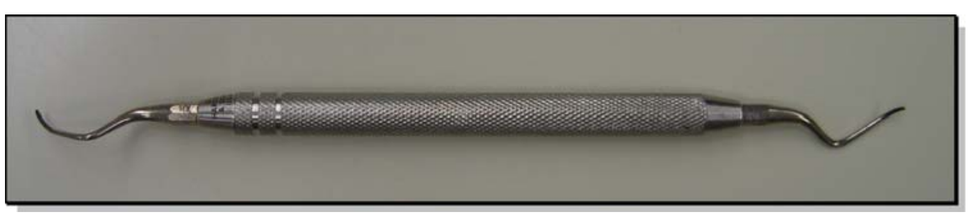
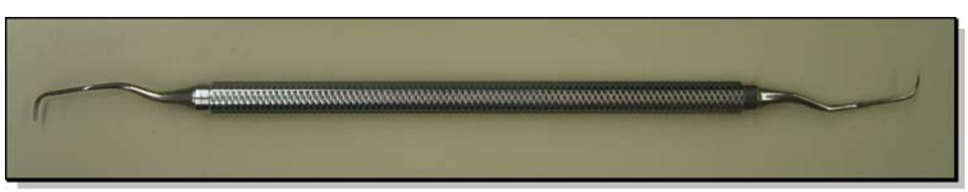


Fig. 9 Periodontal explorer



with both a transparent and an opaque gingiva to contrast the results obtained by the trainee.

4 Implementation of the periodontal simulator

4.1 Overview

Figure 10 shows the simulator setup. The user interacts with the simulator via a stereoscopic display and a haptic device. The stereoscopic display consists of a CRT monitor, capable of a vertical refresh rate superior to 100 Hz, synchronized with a pair of CrystalEyes active stereo shutter goggles from StereoGraphics (http://www.reald.com/scientific/). The haptic device is a [SensAble] 3-DOF (output) and 6-DOF (input) PHANToM Desktop. The simulator allows the trainee to manipulate the position and the orientation of the virtual periodontal instrument by holding a haptic stylus, which has similar dimensions of the ones of the real instruments (Fig. 11). Figure 12 shows the similarities of the user's hand posture holding a real instrument and the haptic stylus. The tip of the virtual instrument is co-located with the haptic gimbal. The system maintains a 1:1 movement ratio between the virtual instrument and the haptic stylus, allowing the trainee to gain fine hand dexterity exactly as needed when working on real patients.

Figure 13 illustrates an overview of the implementation of the haptics-based periodontal simulator. The software has been organized as basically two processes that run concurrently in two different threads on a Windows platform:

- Graphics rendering
- Haptics rendering.

The graphics rendering has been developed on top of Coin, a high-level 3D graphics library that uses scenegraph data structures to render real-time computer graphics. Coin

Fig. 10 Simulator setup

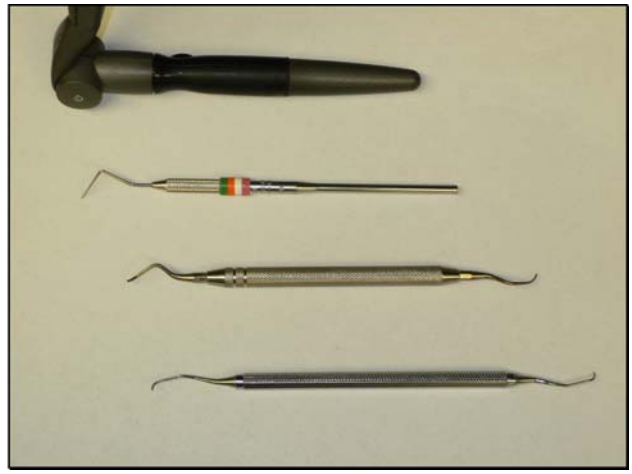


Fig. 11 Scale relationship between the haptic stylus and the real instruments

is an open-source implementation of Open Inventor by Systems in Motion (http://www.coin3d.org/) ideal to develop scientific and engineering visualization applications. The graphics rendering process is in charge of the stereo visualization of the 3D virtual mouth, dental instruments and templates. Coin traverses the scenegraph twice: once for the left view and once for the right view. Using the quad buffer in the graphics card, Coin stores both views in two different frame buffers, which are then displayed by the CRT in synchronism with the shutter goggles.

The haptics rendering has been developed on top of GHOST (General Haptic Open Software Toolkit), which is a cross-platform haptics library commercialized by SensAble Technologies (http://www.sensable.com) for its PHANToM haptic devices. The haptics rendering reads the current status of the haptic device, detects the collisions between the virtual dental instruments and the virtual mouth, and computes the reaction forces to be applied by the haptic device.

Both processes traverse different scenegraph trees stored in memory at different frame rates. While the graphics scenegraph is rendered on the stereoscopic display at 60 Hz overall (30 Hz for each eye in active stereo mode), the haptics scenegraph is rendered on the haptic device at 1,000 Hz to avoid undesired system instabilities that can be felt as vibrations or force discontinuities.

The simulator stores and reads information to and from three files:

- "Mouth.wrl"
- "Mouth components.txt"
- "Instruments.wrl"

"Mouth.wrl" is a set of VRML files containing the 3D geometry (vertices and faces) and their graphic materials (diffuse, ambient and specular coefficients). The 3D model of the mouth was originally purchased from the Viewpoint

Fig. 12 Comparison between handling the real instrument and the haptic stylus

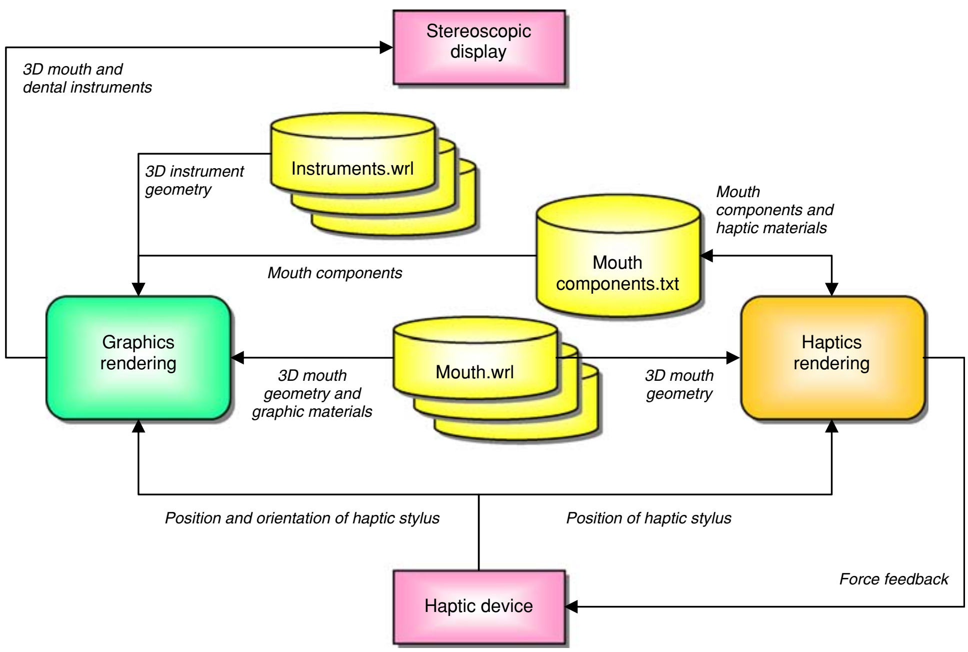


Fig. 13 Overview of the implementation of the periodontal simulator

3D model catalog [by Digimation, http://www.digimation.com], manipulated with 3DStudioMax 6.0 [by Autodesk, http://www.autodesk.com] for a more efficient real-time graphics and haptics rendering, and then exported as VRML files.

"Mouth components.txt" is an ASCII file containing a list of 3D objects that form the virtual mouth: tooth roots, tooth crowns, gingiva and calculi. For each component, the file contains the following fields:

- Name of VRML file associated to the 3D component ("mouth.wrl")
- Stiffness coefficient (spring)
- Viscosity coefficient (damper)
- Static friction coefficient
- Dynamic friction coefficient
- Enabled or disabled haptics

Finally, "Instruments.wrl" is also a set of VRML files describing the 3D geometry and graphic materials of the three virtual dental instruments needed for the periodontal procedure: a periodontal probe, a scaler and an explorer. The 3D virtual instruments were modeled using 3DStudioMax 6.0 and then exported as VRML files.

4.2 Implementation details

Figure 14 shows the graphics and haptics rendering processes in more detail. All processes shown in green are sub-processes of the graphics rendering, whilst the ones shown in orange correspond to the haptics rendering. Note that in addition to the stereoscopic display and the haptic device, the keyboard and mouse have been added to the diagram to

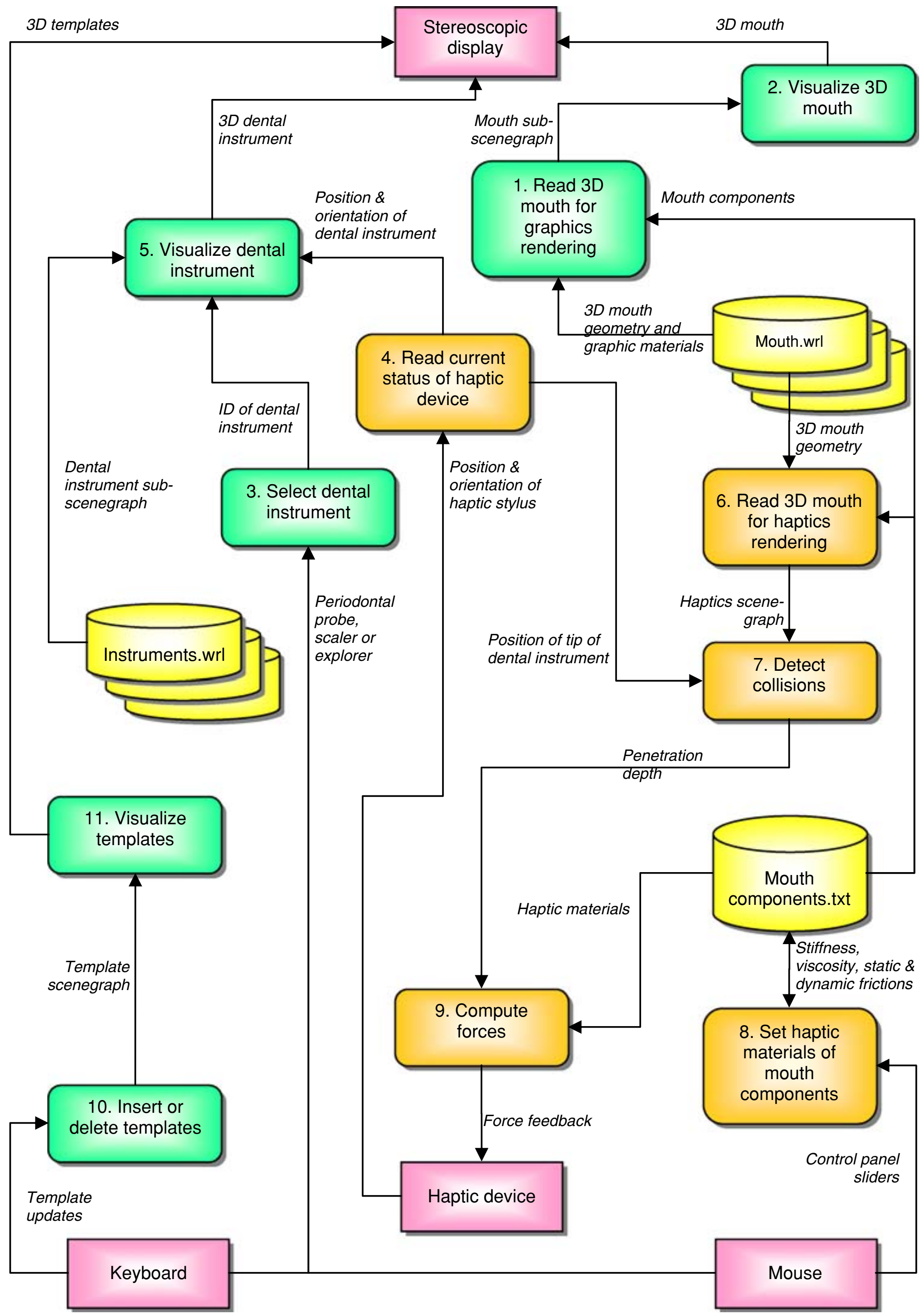


Fig. 14 Implementation details of the graphics and haptics rendering processes

describe the complete user interaction. All sub-processes are described as follows:

4.2.1 *Read 3D mouth for graphics rendering:*

This process reads the filenames of the 3D objects listed in the "mouth components.txt" file. That information serves as a link to the set of "mouth.wrl" files that store the 3D geometry and the graphic materials of the teeth, gingiva and calculi as VRML nodes.

4.2.2 *Visualize 3D mouth*

The sub-scenegraph containing the mouth components is added to the main scenegraph to be rendered by Coin.

4.2.3 *Select dental instrument*

Since each periodontal procedure requires the use of different dental instruments for diagnosis and for treatment of the periodontal disease, the user can select the appropriate virtual instrument before performing the procedure. Figures 15, 16 and 17 show the 3D models of the virtual periodontal probe, explorer and scaler, respectively.

4.2.4 Read current status of haptic device

GHOST computes the inverse kinematics (Craig 1986) to determine the position and orientation of the haptic stylus from the information given by the encoders attached to each servomotor of the haptic device. The position and orientation of the stylus held by the user define the translation and rotation transformation applied to the virtual dental instrument in the 3D virtual environment.

4.2.5 Visualize dental instrument

The 3D geometry and graphic materials of all virtual instruments stored in the "instruments.wrl" files are added to the graphics scenegraph. However, only the chosen instrument is rendered. The user manipulates the haptic stylus as s/he would do it with a real dental instrument, while the 3D representation of the chosen virtual instrument is displayed on the screen in stereo.

4.2.6 Read 3D mouth for haptics rendering

This process also reads the list of objects from the "mouth components.txt" file. Thanks to certain compatibility with VRML format, GHOST is also able to import the 3D geometry from the set of "mouth.wrl" VRML files to store a haptics scenegraph in main memory. Recall that even though the haptics scenegraph (for GHOST) and the graphics scenegraph (for Coin) contain the same 3D objects, they are concurrently traversed at different frame rates by different libraries.

The performance of GHOST collision detection depends on the number of polygons of the 3D models. A high-density polygonal mesh will have low variations of the normals along the surface and thus, will give a smoother haptic feedback at the expenses of a low haptic frame rate. A haptic frame rate significantly lower than 1 kHz will be felt as a vibration when a high stiffness coefficient is chosen to simulate hard surfaces (like the tooth enamel). On the other hand, a low-density mesh will give a higher haptic frame rate needed to simulate hard surfaces, but it could produce undesired discontinuities in areas of large curvature, which are felt as kicks. The following table shows the number of polygons and vertices of each 3D mesh used in the simulator obtaining satisfactory results:

Model	Number of polygons	Number of vertices
Gingiva	6,190	3,313
Roots	10,024	5,076
Crowns	15,220	7,674
Calculi	1,322	671

4.2.7 Detect collision

The 3D position giving by the haptic device allows GHOST to compute a point-based collision detection between the tip of the virtual dental instrument and the 3D geometry of the teeth, gingiva and calculi previously added to the haptics scenegraph. The penetration depth, which is the 3D vector from the surface contact point and the current position of the virtual probe, is calculated by GHOST for all colliding objects in the scene to perform the haptics rendering. In order to achieve high haptics frame rates, GHOST requires rigid polygonal surfaces, which are preprocessed before starting the haptic loop (GHOST 2002).

Fig. 15 Virtual periodontal probe

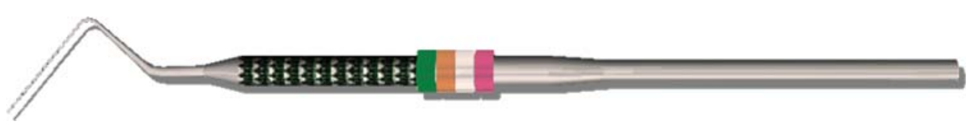


Fig. 16 Virtual explorer

Fig. 17 Virtual scaler

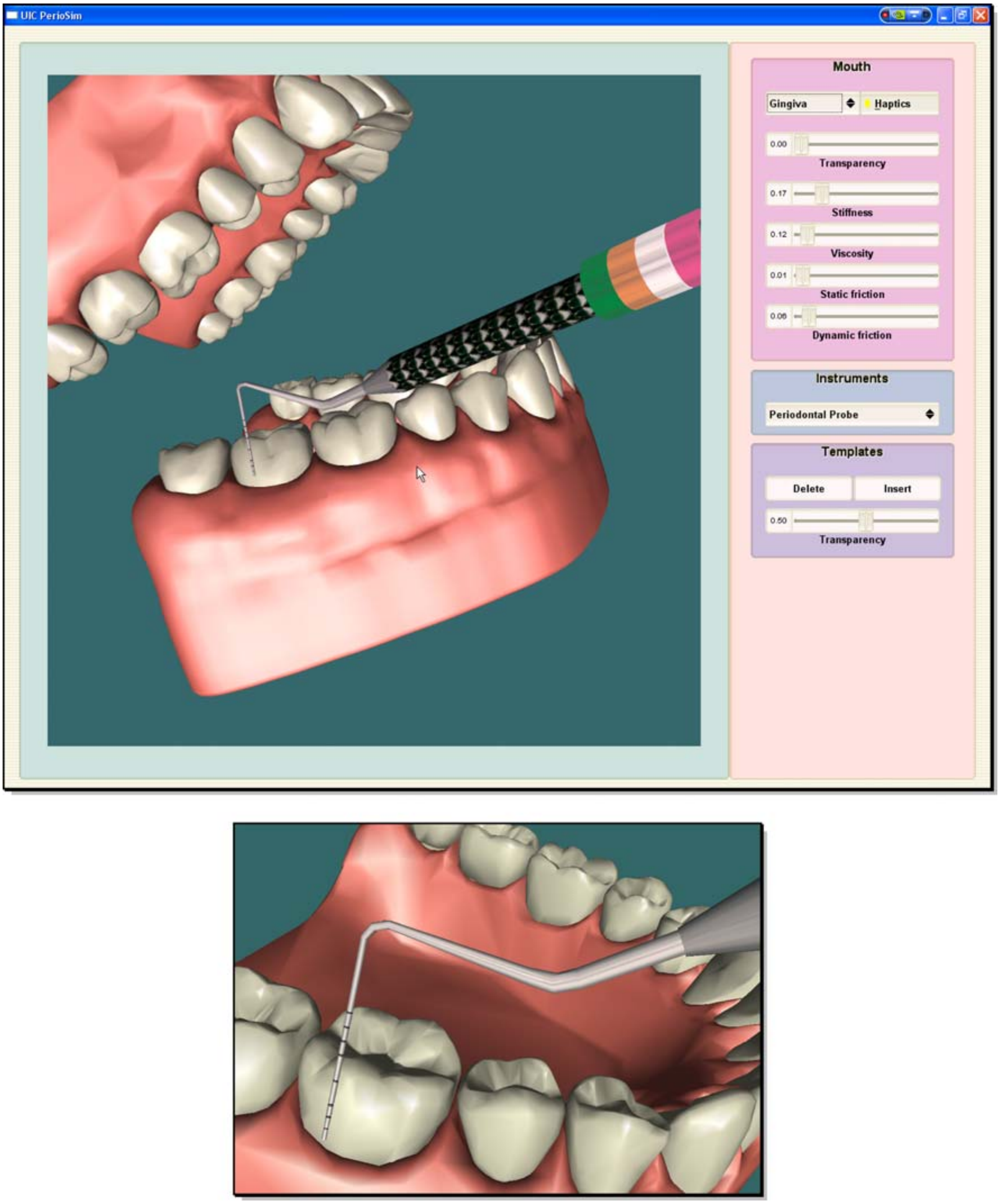


Fig. 18 Measuring pocket depth with periodontal probe

4.2.8 Set haptic materials of mouth components

Since the VRML standard does not provide a way to define haptic materials, the "mouth components.txt" file is used to store four coefficients: stiffness (spring), viscosity (damper), static and dynamic frictions to define the property of the haptic materials of each 3D object. The user can define these coefficients in real time adjusting the sliders in the control panel.

4.2.9 Compute forces

GHOST implements a spring-damper model to compute reaction forces using the penetration depth of the virtual

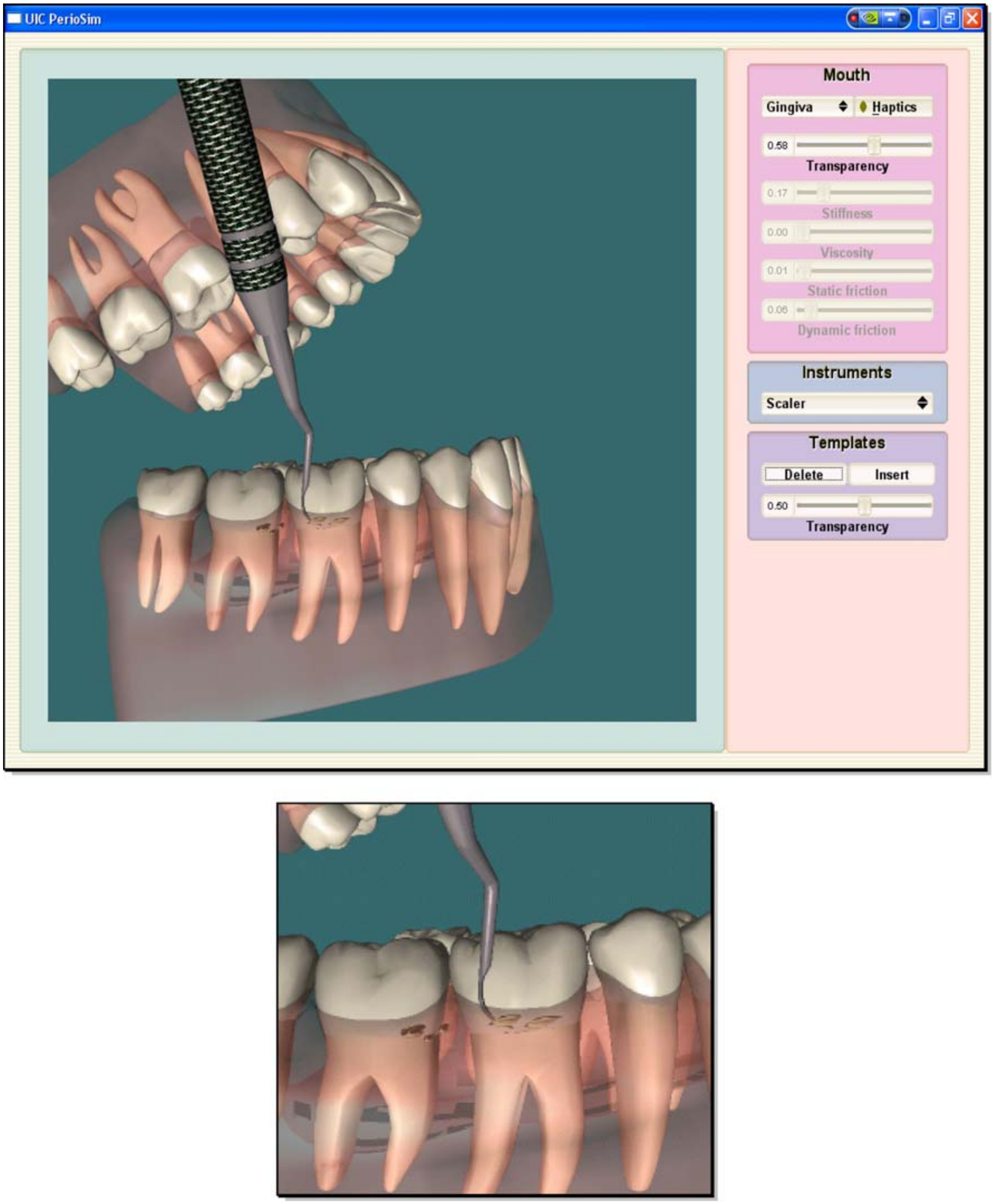


Fig. 19 Calculi being removed with scaler

proxy and the haptic materials of the colliding object. The forces are then sent to the haptic device to give the user the illusion of "touching" the virtual mouth.

4.2.10 Insert or delete templates

Templates are additional virtual instruments that are displayed to guide trainees to learn the correct orientation of the dental instruments while performing the procedure, as a certain way of "scaffolding". The 3D orientation of the dental instrument with respect to the tooth is crucial to succeed in the diagnosis and treatment of a periodontal disease. Because of the complexity of the task, instrument approach is very cumbersome for the instructors to teach to dental students. Templates were incorporated to the periodontal simulator to facilitate that learning process.

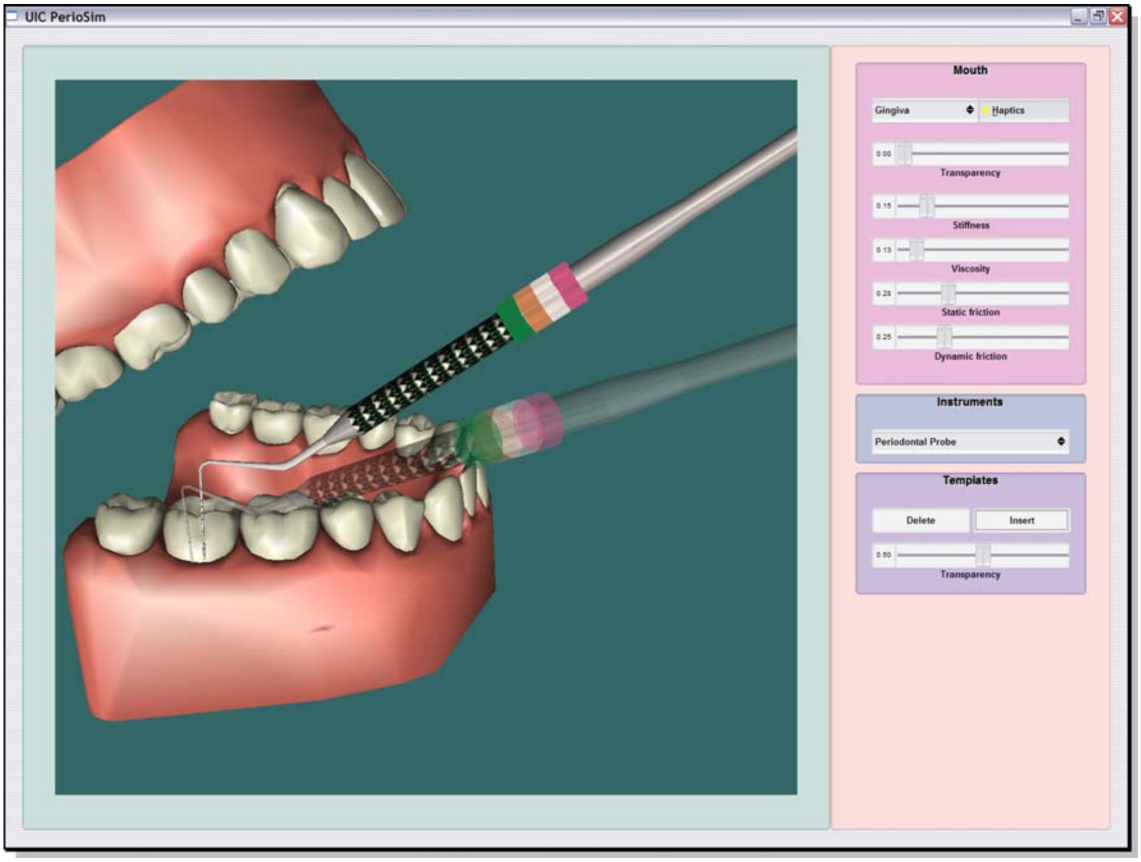


Fig. 20 Periodontal probe and one of its templates showing the appropriate orientation of the instrument

To add a new template, the instructor holds the haptic stylus in the desired position and orientation and then presses the <insert> key. A semi-transparent virtual instrument is then frozen in that particular location. The student can then rotate the virtual mouth to see the desired orientation from any viewpoint. Many templates can be added to the scene to show different approaches while performing the periodontal procedure. Templates can be interactively removed from the scene by locating the tip of the stylus close to it and then pressing <delete> key. Alternatively, templates can be added or deleted clicking on the respective control panel buttons.

4.2.11 Visualize templates

The scenegraph containing all templates is added to the main scenegraph to be rendered by Coin. The transparency of the templates can be adjusted in real time by the user via the control panel.

4.3 Graphical user interface

The periodontal simulator GUI has been developed using the Fast Light ToolKit [FLTK, http://www.fltk.org/], which is a small and modular freely-available cross-platform C++ GUI. It supports 3D graphics via OpenGL® and its built-in GLUT emulation. With FLTK it is possible to incorporate all of the usual widgets to develop applications (menus, buttons, sliders, etc.). It even has a Fast Light User-Interface Designer (FLUID), which is useful to easily draw the user-interface and to define functions, classes and variables as needed. FLUID creates C++ source and header files that can be included in the application.

Figure 18 shows how the user can measure the pocket depth with the markings of the virtual periodontal probe. Figure 19 displays a transparent gingiva to show the presence of calculi attached to two molars and how they can be removed by a virtual scaler during the simulation of the root planning. Figure 20 shows the correct position and orientation of the periodontal probe in that particular section of the tooth by the visualization of a template.

The control panel has a variety of controls, including adjustment of the haptic feel by setting stiffness, viscosity, and static and dynamic friction coefficients, as well as the degree of transparency of the gingiva, roots, crowns, or calculi. The dental instrument can be selected by the control panel, which also permits the instructor to insert a variety of templates to guide the student to position the instrument correctly in a 3D display environment.

5 Use of the periodontal simulator

5.1 Training session

The haptics-based dental simulator is currently being used by the Department of Periodontics at the UIC to train dental students in periodontal probing. The training session consists of the following steps. By moving the haptic stylus, a trainee can move the VR instrument on the tooth surface and feel the crevice or pocket area within the margin of the gingiva (gums) along the root surface of the tooth. Using the control panel, one of three periodontal instruments can be selected for onscreen use: a periodontal probe, explorer or scaler. The 3D virtual periodontal probe can be used to locate and measure crevice or pocket depths around the gingival margins of the teeth.

A trainee can differentiate the textural feel of pocket areas and locate regions of sub gingival calculus. Since the root surface is covered by gingiva, the trainee cannot see the area being probed or the underlying calculus and must depend totally on haptic feedback to identify these areas. This situation corresponds to conditions encountered

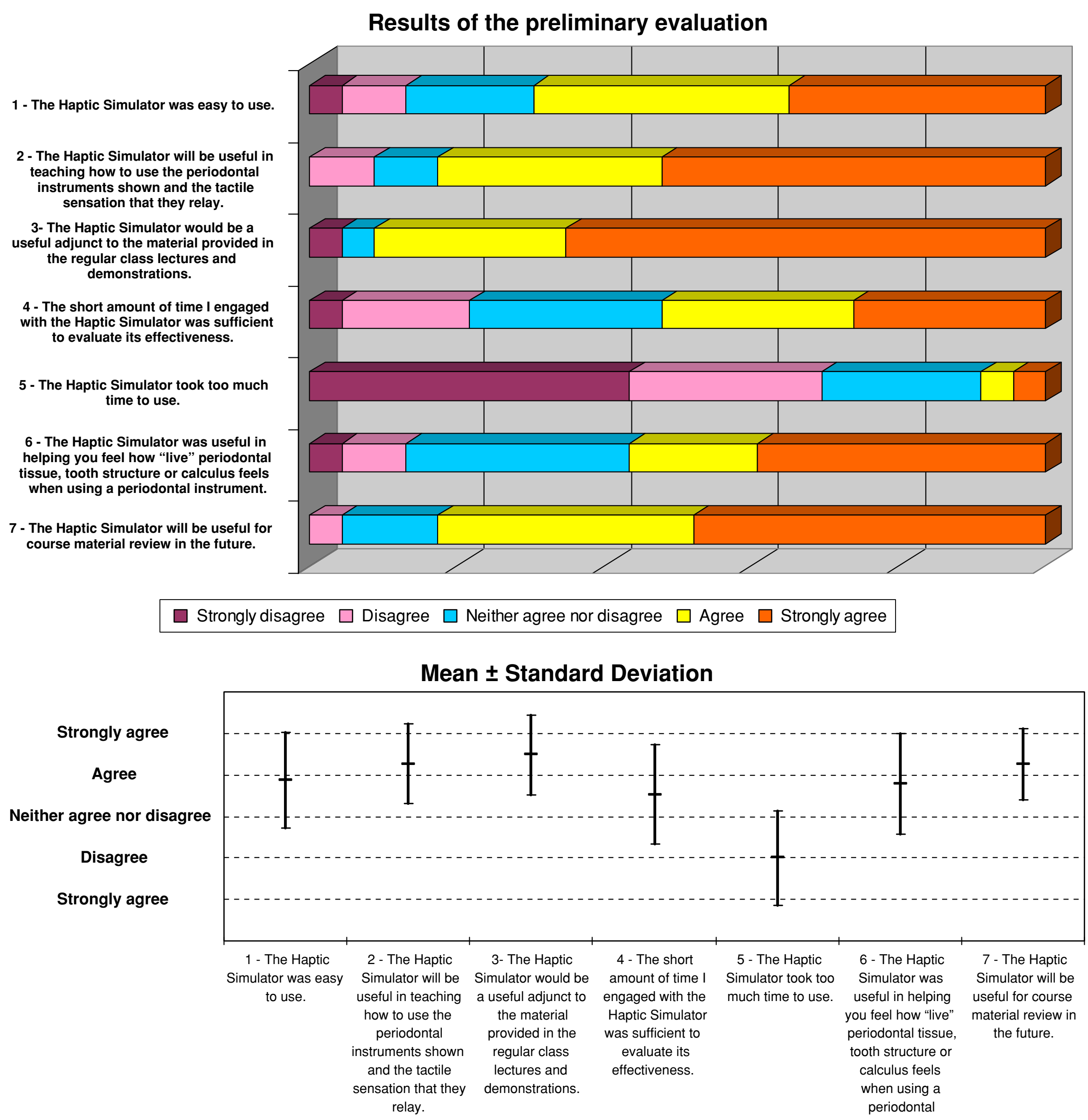


Fig. 21 Results of the preliminary evaluation

clinically. To assist visualization of what he/she is feeling, control panel adjustments can introduce varying degrees of gingival transparency.

Graphical and haptic parameters can be altered by an instructor using control panel adjustments to provide the "feeling" or feedback he/she wishes to impart to the trainee.

The system permits any instructor to generate a diagnostic and/or treatment procedure for student use. Recording of the haptic experiences involves the production of instructor driven trajectories to define correct movements of the dental instrument when performing the periodontal procedure. These recordings can be stored in the system for future use by students and will guide their performance of a procedure. The methods used by an individual instructor to both diagnose and treat a particular procedure can be demonstrated while guiding students to perform the procedure in the same fashion. Note that the instructor need not be present to provide this guidance.

5.2 Preliminary evaluation of the simulator

Validation of the haptics-based periodontal simulator was conducted by the Department of Periodontics at UIC. A seven-question survey was obtained from 18 faculty members and 5 students of the College of Dentistry immediately after a 10-min experience with the simulator. The participants were asked to perform a scaling and root planning on a particular tooth, which takes usually 10 min to perform in a real pacient. The goal of the experiments was to evaluate their acceptance and potential use of the simulator to teach these procedures at the College of Dentistry.

By adjusting the multiple sliders of the control panel on the right of the simulator screen, three clinical instructors in the Department of Periodontics at UIC set the following coefficients of the haptic materials to allow appropriate tactile differentiation:

Model	Stiffness (spring)	Viscosity (damper)	Static friction	Dynamic friction
Gingiva	0.15	0.0013	0.28	0.25
Roots	0.85	0.0023	0.78	1.0
Crowns	0.8	0.001	0.0	0.0
Calculi	0.69	0.0015	1.0	0.0

The survey questions were answered in a 1-to-5 scale, where 1 corresponds to "strongly disagree" and 5 corresponds to "strongly agree". Results of the experiment are shown in the table below (second column shows the number of people that shared the same answer). Figure 21 shows the mean ± standard deviation of the results. Assuming a normal distribution, this interval includes about 70% of the population.

Question	(Disagree) 1 2 3 4 5 (Agree)	Mean
1. The Haptic Simulator was easy to use.	*1 2 4 8 8*	*3.9*
2. The Haptic Simulator will be useful in teaching how to use the periodontal instruments shown and the tactile sensation that they relay.	*0 2 2 7 12*	*4.3*
3. The Haptic Simulator would be a useful adjunct to the material provided in the regular class lectures and demonstrations.	*1 0 1 6 15*	*4.5*
4. The short amount of time I engaged with the Haptic Simulator was sufficient to evaluate its effectiveness.	*1 4 6 6 6*	*3.5*
5. The Haptic Simulator took too much time to use.	*10 6 5 1 1*	*2.0*
6. The Haptic Simulator was useful in helping you feel how "live" periodontal tissue, tooth structure or calculus feels when using a periodontal instrument.	*1 2 7 4 9*	*3.8*
7. The Haptic Simulator will be useful for course material review in the future.	*0 1 3 8 11*	*4.3*

5.3 Analysis of the preliminary evaluation

After the experiment, the Department of Periodontics at UIC reported the following conclusions:

- "The vast majority of users (21) adapted to the system very readily and found it easy to use and navigate."
- "Only five of the responders used their computers for gaming purposes. However, this group adapted to the system faster than did non-gaming computer users."
- "The vast majority (21) were fascinated by the technology and found it difficult to believe that they could feel the object shown on the monitor."
- "Two of the users had a little difficulty with adaptation to the system. But even they were able to adapt and use it after several minutes of practice. Both rated the system lower than others."
- "In the short time span allowed (10 min or less), all users were able to probe the onscreen gingival crevice area and establish its depth. They were able to feel the base of the pocket or crevice."
- "We had difficulty with an oral anatomy instructor exceeding his time limit on the haptic device. He was

so fascinated by the ability of feeling all of the tooth anatomy onscreen that he used the device for 15 min."

- "Several users (10) applied too much pressure in using the haptic device stylus. This resulted in the onscreen probe becoming locked. Unlocking in such a situation is easily performed by pressing on a button on the stylus resetting the program. This reset procedure can be used to record excess pressure using the periodontal probe."

6 Conclusions

This article describes the research and development of a virtual reality dental simulator designed to facilitate the learning of diagnosis and treatment of periodontal diseases. Previous dental simulators focused on different aspects and procedures of the dental education. To the best of our knowledge, this is the first haptics-based dental simulator that was designed exclusively for periodontics. Due to the importance of tactile feedback to perform periodontal procedures, haptics has demonstrated to be not only a helpful assistance in the learning process, but also a fundamental piece of the periodontal simulator to reproduce actual conditions encountered by a Dentist examining real patients. Periodontitis diagnosis and treatment as well as calculus detection cannot be successfully performed without a well-developed sense of touch. That skill cannot be taken for granted, and therefore, it needs to be learnt by dental and hygiene students. The haptics-based periodontal simulator is a small but first step towards that ultimate goal.

The efficient and novel integration between Coin and GHOST succeeded in a perfectly balanced computer load between a high-performance graphics and haptics rendering of relatively complex 3D geometry needed to produce a realistic real-time user interaction.

A subsequent experiment, conducted by (Steinberg et al. 2006) at the Department of Periodontics at UIC to validate the realism of the periodontal simulator for training dental and hygiene students, reported that the prototype haptics-based periodontal simulator was realistic enough to serve as a useful instruction tool with high teaching potential on periodontal procedures.

The periodontal simulator is been continuously improved and tested by the College of Dentistry. Recently, recording and play back of the trainee's performance has been incorporated to the simulator by Steinberg et al. (2007).

6.1 Future research and development

This work offers a basic testbed for a broad spectrum of future development. An object-to-object collision detection could replace the point-based collision detection implemented by GHOST. This would allow a better simulation of the multiple contact points between the dental instruments (like the scaler or the explorer) and the tooth surface. Of course, this would also require the use of a 6-DOF (input and output) force-feedback haptic device as the SensAble Premium 1.5 Phantom to provide resistance considering both the 3D position and orientation of the stylus. However, this is challenging because collision detection among multiple non-convex objects with highly complex geometry and penetration depth calculation are both computationally expensive. Voxmap Pointshell [Boeing http://www.boeing.com/phantom/vps/], and H-Collide (Gregory et al. 1999) are some of the possible alternatives of multi-point collision detection algorithms that will be evaluated in future.

In addition, in order to achieve a higher level of realism, graphics and haptics working volumes should not only match but also be collocated. In this way, the user would be able to "see" and "touch" at the same spot offering a useful tool to develop eye-hand coordination.

More exhaustive experiments of the periodontal simulator, with a larger sample of faculty and students from the Department of Periodontics, will be conducted in future to confirm or refute the results obtained by the preliminary evaluation.

Finally, this work can lead to the simulation of other dental procedures beyond periodontics. Even medical procedures that require the simulation of tactile sensations could be developed based on the current implementation of the haptics-based periodontal simulator.

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