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PerioSim©: Haptics-based virtual reality dental simulator

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Tactile skills training, so necessary in dentistry, is very time-consuming, and requires extensive one-on-one instructor-student interaction. Since many problems arise from the traditional training procedure, the University of Illinois at Chicago (UIC) has set up a research project with the aim of creating a haptics-based, virtual reality dental simulator system (PerioSim©) suitable for training students in various dental procedures. The simulator should facilitate students' development of necessary tactile skills, provide unlimited practice time and require less student-instructor interaction while helping students learn basic clinical skills more quickly and effectively.

Introduction

The term "haptics" refers to the area of robotics dealing with devices designed to simulate pressure, texture, vibration and other sensations related to touch. Recent technological advances have resulted in the production of a variety of affordable haptic devices[1], providing possibilities for vastly improved touch-based human-machine interfaces. In parallel with hardware development, new haptic rendering algorithms[2-6] have been introduced, as well as new software libraries and software development kits[7-10] designed to work with either a particular haptic device or with a variety of them. These developments have facilitated the growth of new haptic applications[7, 11, 12].

One of the areas where this technology is currently being applied is dental education. While traditionally trained students do not feel what the instructor feels nor can they be physically guided by the instructor while performing a procedure, the use of a technology including haptics allows the trainee to enhance learning by feeling and interacting with onscreen objects. An example for the use of this new technology in dentistry is the haptics-based virtual reality (VR) dental simulator (PerioSim) that has been developed at the UIC through joint efforts of the College of Dentistry and College of Engineering. The simulator system consists of a high-end computer workstation with appropriate software, a haptic device, and a stereoscopic computer monitor with stereo glasses. The system is designed for training and evaluation of performance by first-year dental students, hygiene students and practicing professionals in periodontal probing and white spot caries activity. These technological tools being developed at the UIC should aid in solving some of the pressing problems faced by dental schools such as the decreasing pool of dental school instructors, the reduction in time instructors interact with students; furthermore, computer technology can dramatically reduce the need for students to practice on patients.

Initial Development

PerioSim started as an interactive CD-ROM program[13]. The CD provided an easy way to train the students in instrument identification and instrument use, and describe the basic principles and procedures associated with the performance of a specific dental procedure which in this case was scaling and root planing (Sc/Rp). This interactive CD was an essential first step that now provides basic information to all first-year students prior to their introduction to the manikin laboratory. It has been a valuable training aid since 2000.

The second stage of this project involved the development of a real-time training program using the

MiniBIRD® motion tracking device (Ascension Technology Corporation, US-Milton) with audio feedback to help guide students in performing the specific procedure of Sc/Rp on a laboratory model[14]. Sc/Rp involves removal of tooth accretions and necrotic root surfaces, a requirement for maintaining healthy gingival tissues. To learn this procedure, training is necessary. A training program was developed to teach these skills by tracking the direction, speed and motion of the movements made by an expert clinical practitioner during a standard tooth cleaning procedure. Subsequently, the program tracked the motions of the student and provided audio feedback indicating how close the student was to the trajectory of the expert.

While the training program showed promise, testing indicated that this technology had limited application in dentistry. However, the experience of the team of developers of PerioSim with the motion tracking system was crucial in exploiting new technologies using a combination of VR, haptics and robotics which were used for the development of the initial version of the dental simulator program[15-17].

Components – Hardware

The key component of the dental simulator is a PHANTOM® haptic device[1] (SensAble Technologies, US-Woburn), probably one of the most widely used haptic devices today. This force-feedback device allows implementation of touch-based 3D representation through user movements of a small robot-like arm, whose position is tracked by the encoders in the device. Figure 1 shows the structure of the dental simulator and information flow

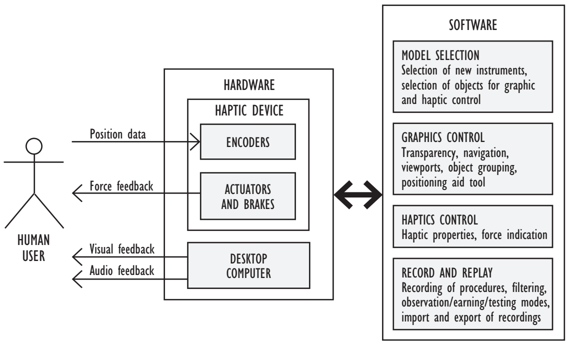

Fig. 1: Structure of the dental simulator and information flow between the human user and the simulator system.

between the human user and the simulator system. Low inertia of the PHANTOM allows the user of the simulator to move freely and explore the virtual environment without feeling any unnecessary or unnatural forces. The tactile sensation is created by the actuators and breaks which in turn are controlled by the simulator software. The PHANTOM haptic device exists in 3-degrees-of-freedom (3-DOF) and 6-DOF versions. In this project the 3-DOF model is used. Due to this limitation only forces (no torques) can be displayed by the device and the haptic interaction is effectively limited to single-point contacts. In this project setup the haptic device is connected to the computer through the parallel port interface. The default haptic update rate provided by the PHANTOM is 1 kHz.

Another major component of the simulator is a Dell Precision 530 Xeon Workstation (Dell, US-Austin), along with an NVIDIA Quadro FX 3400 Graphics Card (NVIDIA, US-Santa Clara). A high quality Crystal Eyes® monitor with Crystal Eyes® stereo glasses (StereoGraphics Corporation, US-San Rafael) is used to view 3D graphic images generated on the workstation. An additional flat panel monitor (Dell) is used to display instructions for using the simulator and performing certain tasks (Fig. 2).

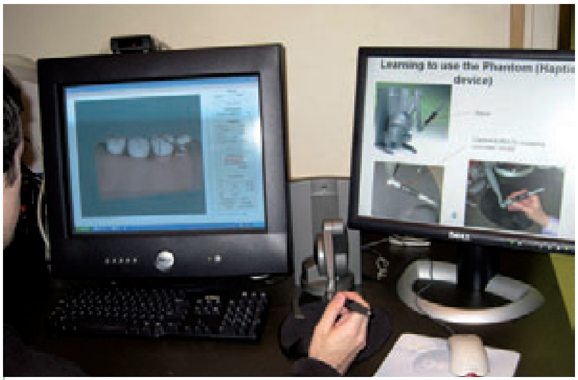

Fig. 2: The system uses two computer monitors with the haptic device placed between them. The monitor on the left is stereoscopic showing the simulator images and the control panel while the monitor on the right provides instructions.

Such demanding graphics applications were formerly run on expensive graphics supercomputers but can now be used on a regular desktop PC. The lower cost and compact size of such systems is an asset that allows haptics-based virtual reality technology to be widely used in a broad range of applications including dental education.

Components – Software

The main program is written in C++ programming language using several specialized libraries. The main library that enables the use of the haptic device in the program is the General Haptic Open Software Toolkit (GHOST®, SensAble Technologies)[7]. This is a general cross-platform haptic application programming interface (API) which processes the interaction with the haptic device by constantly monitoring for collisions between the stylus and the objects in the virtual environment and computes the force to be displayed by the haptic device when a collision occurs. This reaction force creates an illusion of touching the object. The API allows developers to create haptic applications by providing simple objects whose physical properties like location, mass, friction and stiffness can be easily adjusted.

In order to display the objects on the screen, the Coin3D (Systems in Motion, NO-Oslo) library is used, an API for 3D graphical rendering featuring scene-graph data structures. The two API data structures (GHOST and Coin3D) have to be synchronized, so that visual and haptic feedback information refer to the same virtual scene and are therefore consistent. Freely available Fast Light Tool Kit (FLTK) (Digital Domain, US-Venice) provides various common graphical user interface (GUI) elements such as buttons, menus, dials and various selectors.

In the initial version of PerioSim, the 3D VR model teeth, obtained from Viewpoint Corporation (US-St. Rose) were used showing upper and lower dental arches with a full compliment of teeth (32 in total) and their adjacent gingival tissue. Since these 3D models were not sufficiently detailed and had graphical flaws resulting in low realism of haptic interaction when running the program, new finely detailed models were developed (Illumen Studios, US-Evanston). Thus, Version 2 of the simulator utilizes more anatomically accurate 3D models of a 4-tooth mouth segment (lower right second bicuspid through lower right third molar) containing gingiva, bone and teeth depicted in Virtual Reality Modeling Language (VRML) (Fig. 3). VRML is an open standard for representing 3D interactive vector graphics. Anatomically accurate 3D model depictions of several different stages of periodontal destruction and caries are shown. The trainee has unlimited practice time to familiarize her / himself with the visual as well as tactile aspects of both periodontal disease and very early dental caries (white spot lesions). The fact that the anatomical models have been developed in the VRML format makes them easy to reuse in other applications and share over the Internet. This format also allows for easy modifications of the model in the future. Additional features such as bone pathologies, gingival pathologies and calculus, can be modeled in VRML format, and overlaid within the main model.

Fig. 3: Lateral view of the 4-tooth segment of a lower right dental arch with no transparency on the left side and 31 % gingival transparency on the right side.

Simulator Functionality

The simulator consists of several functional blocks realized in its software. These include model selection, graphics and haptics control as well record and replay functionality (Fig. 1).

Model Selection

Over ten dental instruments are currently available in the simulator for haptic use. These include Williams, UNC15 and CP12 periodontal probes, Shepherd's hook, periodontal explorer, and Gracey scaler. New instrument, gingiva, teeth and bone 3D VRML models can easily be added when desired. These 3D models are geometrically and anatomically accurate and constructed to the developers' specifications. Once 3D VRML models are constructed they can easily be configured for use through a special configuration file, and observed and felt in the Perio-

Sim program through a haptic device. This functionality was incorporated in Version 2 of the software in order to make it more versatile and allow the user to handle most routine adjustments to the simulator without any need for a programmer. This was also done to allow the simulator to be used for any training system, be it medical or non-medical.

Selected instruments can be moved around in 3D through the use of the stylus attached to the haptic device. The user can also rotate the model in one of the three planes (XY, YZ, XZ) and move the model along one of the three axes (X, Y, Z) using the navigation control block (Fig. 4).

Graphics Control

In the main window of the simulator the user can see the full-screen 3D model of a mouth section along with the main control panel. The main control panel can be hidden by activating the F1 function key and can be reactivated by pressing the F2 function key (Fig. 4, left side). The main control panel contains a variety of controls for navigation which include options to view gingiva, teeth and bone. The trainee can induce varying degrees of transparency of the selected objects using a slider bar (Fig. 4, right side).

In the simulator, objects can be logically grouped into categories, or groups. Initially, two groups are formed: gingiva and bone in one group and teeth in the other. The user has the ability to turn the visibility of the grouped objects on or off. Special buttons allow the user to switch immediately to buccal, occlusal or lingual views of the model. Also available is the positioning aid tool which allows the trainee to observe for two seconds the occlusal view of the entire scene, which includes the dental instrument. In many cases this aids the user, especially a novice, to achieve the proper alignment of the instrument for a specific procedure.

Haptics Control

In the main window of the simulator the user can control the haptic properties of the simulation process (Fig. 4, right side). This includes the basic ability to turn haptics on or off for each selected object.

A force magnitude indicator (in vertical grams-force being applied) allows the student to feel the small amount of force used for periodontal probing. Once the required force of 20 gf (0.196 N) is reached, the indicator changes color from white to red. This sends a visual cue to the student to reinforce the experience. It is well documented that the force of around 20 gf (0.196 N) is all that is required for periodontal probing[18, 19]. However, it is difficult, if not impossible to describe to a student how much force this is. With the use of a haptic device, the exact force reading can be viewed and felt by instructor and student, thus greatly enhancing the learning experience.

The additional haptic parameter panel (Fig. 4, left side) can be viewed as well. It contains the four sliders controlling several haptic parameters for either teeth, gingiva or bone. Figure 5 shows the periodontal probe positioned properly as viewed interproximally from the occlusal showing white spot lesions on the occlusal of the molars. Table 1 shows the parameters controlled by the haptic parameter panel (Fig. 4, left side). These parameters can be altered separately for each object.

Viscosity	A measure of the resistance of a material to deform under shear stress.
Stiffness	The resistance of a material to deflection or deformation by an applied force.
Static friction.	Friction is the force that opposes the relative motion or tendency toward such motion of two surfaces in contact. Static friction occurs when the two objects are not moving relative to each other.
Dynamic friction	Occurs when two objects are moving relative to each other and rub against each other.

Table 1: Parameters controlled by the haptic parameter panel.

Record and Replay Functionality

An important functionality implemented in the simulator is its 3D recording (and subsequent playback) capability allowing the user to record the motion of an instrument for up to 5 minutes. This allows an instructor to create short scenarios of procedures,

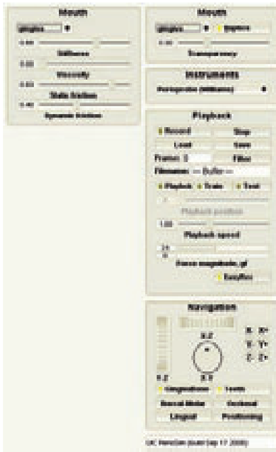

Fig. 4: Four-slider haptic parameters control panel (left side) to control the feel of the gingiva, teeth and bone. On the right side is an enlarged view of the main control panel indicating the transparency, instruments, playback, and navigation controls.

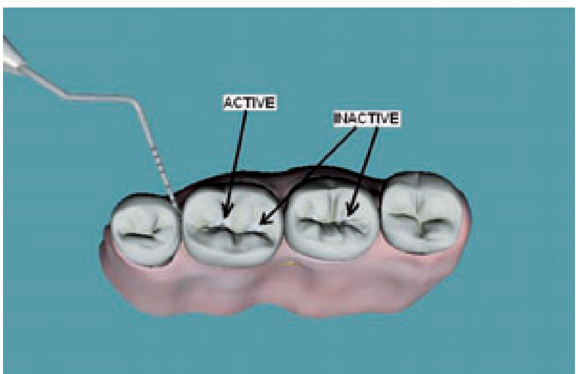

Fig 5: Occlusal view of periodontal probe in the interproximal area. Also seen are views of active and inactive white spot lesions. Haptics is required to differentiate active from inactive.

such as periodontal probing, which can be stored and played back by the student at any future time on the computer, either from any storage media or over the Internet.

A recorded 3D motion can be filtered to eliminate or decrease any extraneous movements using a built-in 3rd order Butterworth filter[20] with an adjustable cut-off frequency. The recorded motion can be saved in a specified file, and then exported and viewed on any other PC using the developed viewer. The viewer is essentially a much simplified version of the simulator without the haptic capabilities. The recorded 3D motion can be played back in one of the three modes:

- Observation mode: During playback the trainee can cradle the stylus, observe an image of the original instrument and view the on-screen instrument movement. A recorded procedure can be paused and the 3D viewing component of the program permits playback from any angle, so that the user can observe various views of the instrument, tooth and gingival relationships during a procedure. Various degrees of transparency can be applied to this model.

- Training mode: The trainee holds the haptic stylus and actually, physically feels it guiding his / her hands through exactly the same movements while encountering the same tactile feedback, felt by the instructor. In this mode the recorded graphics data is displayed as in the observation mode, so the trainee sees two instruments: the main instrument that he / she controls and the green transparent image of the instrument going through the recorded procedure (Fig. 6). A haptically rendered guiding force is applied that drags the user-controlled instrument to the desired recorded position. Auditory cues are given if the rotation of the instrument deviates too far from the recorded rotation.

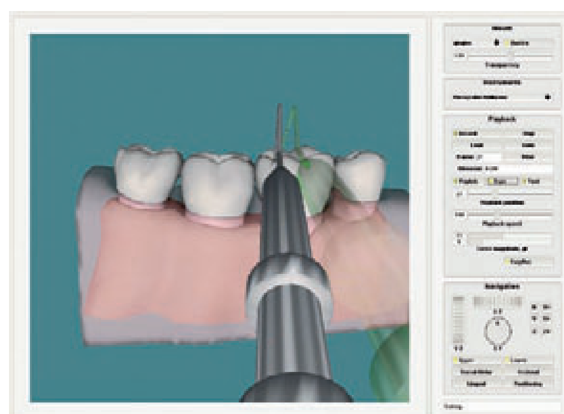

Fig 6: In the training mode the user tries to match the position of the instrument (shown in gray) with the recorded position of the reference instrument (shown in green and transparent).

- Testing mode: The user is being tested on his / her ability to repeat the recorded procedure. No recorded graphics or haptics data is displayed (although either or both of these capabilities could be turned on if needed). The trainee performs the same procedure recorded by the instructor and receives instant grading of how well he / she performed the procedure. An aggregate score, or grade, on a scale from 0 to 100 is displayed after the trainee finishes the procedure. If the recorded trajectory is followed perfectly, the trainee receives the perfect grade of 100. Otherwise, points are deducted for deviations of the trainee's trajectory.

In the observation and training modes it may be desirable to slow down the playback so that the student can better absorb the unfamiliar technique or even stop it completely, so that he / she can, perhaps, rotate the model and take a look at the position of the instrument from various angles. In the simulator it is possible to adjust the speed of the playback if needed.

Reality Validation

Interaction with the members of the dental teaching faculty was needed on a regular basis during the development of the PerioSim to identify the strengths and weaknesses of the simulator from a clinician's point of view. The result of this interaction was recently assessed in a study[21, 22] to validate the realism of version 1 of this system and determine which components require further development. To validate the reality of version 1 of the dental simulator PerioSim, 30 male and female volunteers, experienced dental and hygiene instructors from a variety of clinical areas were used.

The study was designed to evaluate whether faculty considered the PerioSim realistic and useful for training and evaluating basic procedural skills of dental and hygiene students. Faculty / practitioners found the images very realistic for teeth and instruments, but less so for gingiva. Tactile sensation was realistic for teeth but not so for gingiva. The probing instruments were realistic and the instrument markings easy to read. Faculty believed the simulator had a high training potential, were enthusiastic about its potential for evaluating students' basic procedural skills and anticipated incorporating this device into teaching. The study suggested that the self-contained teaching and training program in periodontal probing should aid students in the development of necessary dental tactile skills.

Discussion

Haptics opens up exciting opportunities for computer-assisted teaching and training that are vastly superior to what can be achieved using only audio and video aids. The technology described in this paper enables the students to develop the necessary skills while minimizing the instructors' time and effort as well as the time students have to practice on patients.

The dental training simulator is an innovative addition to dental education thanks to the use of haptics. It allows creating a more life-like, self-contained training program in which the trainee can interact with and be physically guided by onscreen objects. The device is currently designed for teaching, training and testing performance by dental students, hygiene students and practicing professionals attempting to learn or enhance their periodontal probing skills.

The haptic device currently used in PerioSim has 3 DOF which implies that it can only simulate a single point of the instrument in contact with the surface. In other words, the current system cannot prevent the instrument whose tip touches a surface of an object (e. g. teeth, gingiva) from being rotated into the object around the contact point. The team of developers is currently investigating this problem, it could be solved by using a 6-DOF haptic device together with better collision detection, faster processing of information, and the creation of new more realistic haptic rendering algorithms[23]. Further enhancements such as incorporating a second PHANTOM device and adding a VR, 3D image of a human head to allow trainees to use both hands on the screen are planned as well. In spite of these drawbacks, both instructors and students can adapt easily to the present simulator and use it effectively. This leads to the conclusion that the simulator and its ability to afford unlimited practice time is an important new development for dental education.

In the future this system will be used for training in other aspects of periodontal procedures, carious lesion evaluation, evaluation of restorative procedures, diagnosis of pathological conditions in the oral cavity and other areas of diagnosis and clinical therapy in dentistry and medicine.

While this paper focuses on the haptic aspect of the simulator, 3D visualization is a very important aspect of the simulation process. The visualization and haptics complement and enhance each other. While only the tip of the Shepherd's hook explorer, periodontal explorer and periodontal probe can be haptically sensed, the 3D graphics helps to create a realistic experience for the user. In general, graphics, haptics, and sound appear to all play an important role in training[24].

Conclusions

The haptics-based VR periodontal probing simulation program is in preliminary development and continues to evolve as advances in computer technology are incorporated and programming enhancements are implemented offering additional functionality for the end users. The VR periodontal probing haptic simulation program should facilitate students' development of necessary tactile skills, provide unlimited practice time and require less student-instructor interaction while helping students learn basic clinical skills more quickly and effectively.

The bibliography can be requested from the editorial office.

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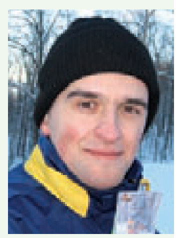

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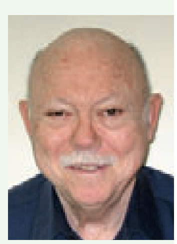

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