VIRTUAL REALITY INTELLIGENT DENTAL SKILL TRAINER

by

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Computer Science

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Abstract

Dental students devote several years to the acquisition of sufficient psychomotor skills to prepare them for entry-level dental practice. They usually rely on traditional training methods, for instance, practicing on dental mannequins with plastic teeth or on live patients. After a training session, dental experts assess students' dental outcomes based on subjective measures. These traditional methods of skill training and assessment, however, have limitations such as the lack of challenging dental cases, limited availability of expert supervision, and the limited level of detail in human expert assessments. In addition, practice on live patients poses ethical concerns.

To address these issues, this dissertation presents a dental training system that provides a simulated yet realistic virtual reality (VR) environment with haptic feedback. With this system, dental students are able to practice dental procedures without need for expert supervision and at little or no incremental cost. The system can monitor important features of the procedure, objectively assess the quality of the performed procedure, and provide feedback on the student's performance. Incorporated with the system is an intelligent training module that allows students to practice dental procedures with varying levels of guidance.

Based on a number of human studies, we find that the realism of the graphics and haptics is acceptable for virtual training. We also find that the accuracy of the objective performance assessment and the quality of the system's training feedback are high. Moreover, students and experts agree that the intelligent training module is a valuable tool for independent training. These positive results are promising and support the applicability of the simulation system as a supplemental training tool for dental surgical skills.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

1.1 Background and Motivation

The goal of clinical skills training is to help trainees acquire skills needed to perform clinical procedures effectively and efficiently. Skills training in medical and dental schools motivates students to become skillful professionals after years of fundamental learning from classroom lectures and textbooks.

Dental education, of all the health professions, is a discipline in which a significant proportion of pre-clinical training is dedicated to teaching fine clinical psychomotor skills to achieve high level of precision and coordination in a very small operating field. The traditional dental skills training class consists of a demonstration by a dental educator in front of a group of students. This apprenticeship approach is called *See one, do one, teach one* (Gorman, Meier, Rawn, & Krummel, 2000; Roberts, Bell, & Duffy, 2006). Students observe experienced dentists and then practice under close supervision before being able to train other students (see Figure 1.1). This method of training has been carried out for decades (Bader, 2004). Apart from direct interaction with live patients in the presence of an expert, alternative sources of training include working with physical models of a patient's head with mouth and teeth (the mannequin or phantom head, see Figure 1.2), and real teeth extracted from patients.

These traditional training methods, however, have their limitations. In master-apprentice skills training, it is difficult to train a group of students efficiently. As a result, students spend most of the time as observers rather than as active participants. Moreover, this type of training demands time and effort from dental faculty, who are also occupied with other duties. Training directly with patients also has distinct problems. While it is obviously the most realistic method, it raises ethical concerns for patient safety. In addition, it lacks practice on uncommon conditions not normally found in volunteer patients. Practicing on extracted teeth is safer than practicing on real patients, but the problem of availability still applies. Finally, the problems of training with disposable plastic teeth on a phantom head include high incremental costs and a limited number of procedures that can be performed. All these limitations could eventually prevent dental students from having enough practice sessions for skills acquisition.

One promising solution to these problems is simulation-based dental training. Earlier dental simulators were constructed on top of a phantom head with an additional optical tracking system. The tracking components include infrared emitters attached on dental instruments and an infrared camera to track their movements for later assessment. However, phantom-based simulators still suffer from limited number of procedures to be practiced, restricted availability, and cost ineffectiveness. An example of this kind of simulator is DentSim from DenX Ltd., which is commercially available at around $70,000 per unit. Another kind of simulated dental training is virtual reality (VR) simulation. Virtual reality is a computer-generated representation of an environment that allows a user to interface, interact with, and integrate different types of sensory inputs that simulate real-world experience, thus giving the impression of actually being present (Riva, 2003). For decades, the use of computer-

Figure 1.1: Traditional apprenticeship approach in dental skill training. Students observe a demonstration by a dental educator (photo courtesy of U.S. Air Force).

based simulation has been shown to be effective by the aviation industry for pilot training. With recent advances in computer hardware and VR technology, cost-effective VR simulators for complex simulation such as surgery have been introduced.

1.2 Overview of the Dissertation

1.2.1 Virtual Reality Environments in Surgical Training

The advantages of VR simulators for surgical training are that the students are able to practice procedures as many times as they want at no incremental cost and that the training can take place anywhere. Moreover, practice sessions are not carried out on live patients as the simulators can themselves provide realistic three-dimensional models for practice. The simulated models are either generated synthetically or reconstructed from computerized tomography (CT) imagery of a patient's teeth for better realism. VR simulators are also more effective than the phantom heads because they can simulate almost all surgical cases. Therefore, uncommon cases that are rarely found in patients or those that require repetitive practice to achieve perfection can be readily accessible by students. Minimally invasive surgery (MIS) was among the first surgical disciplines to employ VR simulation in basic skills training (Satava, 1993).

Initially, acceptance of VR training simulators has been slow due to their cost and the unrealistic appearance of the simulated environments (Gallagher & Ritter, 2007). This is gradually changing with advances in computer hardware, software, and human-computer interaction. Recently the realism of VR simulators has increased with the introduction of haptic interface devices that provide tactile

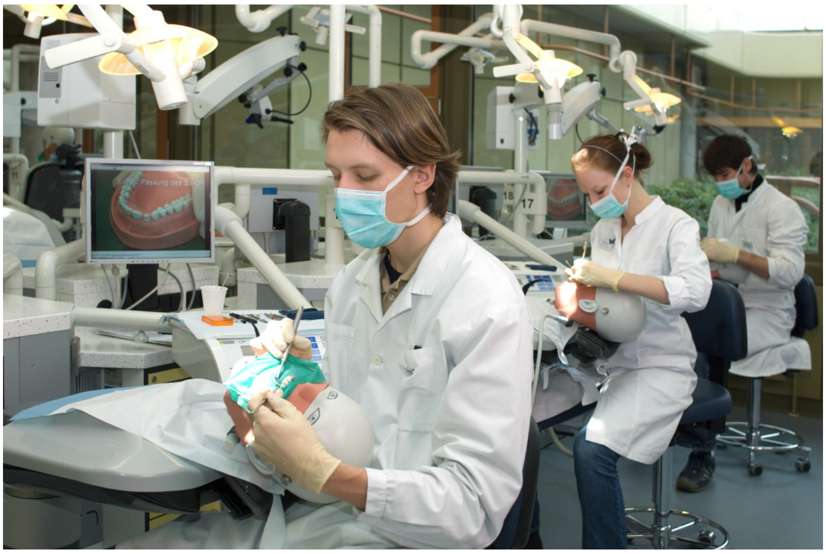


Figure 1.2: Dental students practice procedural skills on phantom heads (photo courtesy of University Hospital Heidelberg).

sensations to the users (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004). Haptic devices in surgical simulators allow students to virtually touch and feel objects such as surgical tools and human organs, and to perform operations like pushing, pulling, and cutting of soft or hard tissue with realistic force feedback.

1.2.2 Performance Assessment in VR Surgical Training

Proper assessment of the quality of a performed procedure is crucial for students to track their progresses, to achieve better results, and to improve their skills and competencies. While VR simulators enable repetitive practice sessions, if students are allowed to practice without receiving feedback on their performances, they could lead to poor results. Traditionally, performance assessment is conducted by having an expert surgeon observe a student's procedure and the final outcome. Because this requires a significant amount of time of an expert who has many demands on his or her time, it imposes a limitation on the amount of guided practice that students obtain. VR simulation can be a means to increase the amount of guided practice for students if the simulation can be equipped with algorithms to assess student performance for *outcome* and *process*.

The purpose of *outcome assessment* is to verify that a student has knowledge of a desired outcome and to verify whether he or she can achieve it. Assessment of surgical *process* usually involves instructors to observe operations in real-time or from recorded videos and guide students accordingly. This task requires great time and effort. Moreover, the level of detail of human expert assessment is also limited. In a VR training simulation, the associated data on how surgical steps are performed and data about the environment can be recorded precisely and analyzed further, making them extremely useful for process assessment.

1.2.3 Tutoring Feedback and Training Strategy

While performance assessment is crucial in identifying student's strengths and weaknesses, assessment alone tells students very little about how to improve their performance. Novice students are normally dependent on instructors to supervise and provide feedback (Hauser & Bowen, 2009). Thus, to add more educational value and reduce the time and effort required for instructors to supervise and tutor trainees using the dental simulator, the system should be able to provide valid and reliable tutoring feedback with quality comparable to that of human tutors. Moreover, the training simulators should incorporate training strategies which are not available in traditional methods such as analysis and visualization of difference between novice and expert performance, or guiding a correct force pattern to a novice with haptic feedback.

1.2.4 Transfer of Acquired Skills to the Clinical Environment

Another important stage in developing an effective VR surgical simulator is to validate that students can transfer acquired skills from the simulator to the actual operating room. This is probably the most important goal in surgical skills training.

1.3 Review of Related Work

1.3.1 Virtual Reality Simulation in Dentistry

VR training simulators with haptic feedback in dentistry have started to gain attention in the last few years. Luciano (2006) developed PerioSim, a VR system that allows trainees to practice diagnosing and treating of periodontal diseases. The simulated procedure involves gum pocket depth measuring and calculi removal from the infected pocket with a virtual periodontal probe and scaler. These virtual instruments are controlled by a haptic device to enable tactile sensations essential to periodontal training. Wang et al. (2005) proposed a cavity preparation simulator that allows cutting of tooth material. In their work, the virtual tooth is represented as a triangle mesh and the virtual dental burr as a simplified analytical sphere. They implemented vertex deformation technique for material removal during tooth cutting. Other related work in VR dental simulation uses the volumetric approach, as opposed to surface approach, for tooth representation and haptic rendering (L. Kim, Hwang, Park, & Ha, 2005; Yau, Tsou, & Tsai, 2006; Yau & Hsu, 2006; Forsslund, Sallnas, & Palmerius, 2009; Wu, Yu, Wang, Zhang, & Wang, 2009; Konukseven, Onder, Mumcuoglu, & Kisnisci, 2010).

Algorithms and techniques in VR dental simulators, especially in dental drilling/cutting, are relatively similar to those applied in VR temporal bone drilling (Petersik, Pflesser, Tiede, Höhne, & Leuwer, 2003; Agus, 2004; Morris et al., 2006). However, while bone drilling usually requires only spherical-shaped cutting burrs (which also helps simplify cutting algorithms), dental cutting utilizes many more shapes and sizes for dental drills. These various burr shapes require more complicated algorithms for graphics and haptic representation and rendering.

Moreover, little work has been done to obtain evaluations of the realism of the simulators from dental students and experts or to obtain feedback from these potential users. Recent studies by Konukseven et al. (2010) and Gal et al. (2011) demonstrate that dentists and dental students were motivated to use their proposed dental simulation systems. Their questionnaire results also show positive responses for realism and usefulness of the simulators.

1.3.2 Automatic Surgical Performance Assessment

Only a few techniques have been proposed regarding automatic assessment of *outcomes* in surgical simulation. Sewell et al. (2007) developed a temporal bone removal simulator and computed average bone removal probabilities to find areas normally removed and not removed by experts and then compared these with the outcomes of novice practice. Their results show that this metric correlates with instructors' subjective ratings. In their wisdom tooth extraction simulator, Forsslund et al. (2009) calculate and report the amount of bone removed in each structure before extracting a tooth by a student compared to an expert. However, the same amount of bone removal does not imply the same cut shape or area. Results from these studies suggest that automatic dental outcome assessment is still a challenging problem yet to be solved.

There has been some work on automatic surgical *process* assessment. Rosen et al. (2002) present a technique for objective evaluation of laparoscopic surgical skills using hidden Markov models (HMMs). The models are based on force/torque information obtained from a surgical robot. Lin et al. (2006) collected various measurements from the da Vinci surgical robot while an operator performed a suturing task. The aim of their study was to automatically detect and segment surgical gestures, which is a part of their ongoing research on automatic skills evaluation. Sewell et al. (2007) present a number of metrics specific to automated evaluation of a simulated mastoidectomy. These metrics include, for example, the amount of bone removed during proper and obscured visibility, the amount of bone removed while the force applied is too high or the drill is moving too fast. Some of these metrics are shown to be correlated with expert's assigned scores. While it has been shown that recording of data on how surgical steps are performed is very useful for process assessment in many surgical fields, none of the existing work on VR dental simulator provides this functionality.

1.3.3 Tutoring Feedback and Training Strategy in Surgical Simulations

There has been recent work in generating tutoring feedback in surgical simulations. Morris et al. (2006) implemented a haptic mentoring module that allows students to experience forces from a remote expert's interaction in their bone surgery simulator. Similar functionality is provided by a periodontal simulator that allows an instructor to record scenarios of periodontal probing for students to replay (Kolesnikov, Steinberg, & Zefran, 2009). Sewell et al. (2008) visualize metrics for visibility testing, learning of safe forces, and other relevant metrics on the simulator console after a training session in their mastoidectomy simulator. With little related work in the dental domain, a study to find effective feedback generation techniques and tutoring approaches for VR dental simulators is needed.

1.3.4 Skills Transfer from VR to Clinical Environments

There are a number of studies on transfer of skills in minimally invasive surgical simulators (Seymour et al., 2002; Kanumuri et al., 2008) and temporal bone drilling simulators (Sternberg et al., 2007). Most of this work finds that sufficient training with simulators improves operating room performance. However, little or no work has been done on the transferability of skills from VR dental simulators to clinical situations.

1.4 Contributions

The main contributions of this thesis can be divided into three areas: simulator development, performance assessment, and intelligent tutoring.

1.4.1 VR Dental Simulators for Crown Preparation and Access Opening

The first contribution of this thesis is the development of VR dental simulators with haptic feedback for crown preparation and root canal access opening. Crown preparation is the first step in dental restoration. It involves cutting the tooth with dental burrs to make space for restorative materials. In the crown preparation simulator, we utilize a surface-based approach in which the tooth and dental burrs are represented as surface meshes and cutting is simulated using surface deformation. The cutting technique and force computation are adapted from the algorithm for a spherical cutting burr (Wang et al., 2005) to handle the cylindrical burrs frequently used in crown preparation. We had dental students evaluate the realism of this simulator and received encouraging results as well as constructive suggestions for further improvement.

After the crown preparation simulator, we developed a root canal access opening simulator by introducing a volumetric approach to data representation and haptic rendering. Access opening is the first step in root canal therapy. It involves drilling down to the pulp chamber where the nerve tissue resides. The volumetric approach allows us to simulate complicated cutting operations which involve drilling into different tooth structures and feeling different hardness. We extend the work on temporal bone drilling simulation by Morris et al. (2006) to allow for more complex, non-spherical tools, and we improve upon the efficiency of their surface reconstruction algorithm by using efficient iso-surface mesh generation techniques. Our enhancements support realistic, stable cutting simulations and removal of tooth materials. We conducted a human study and found that the system provides sufficiently realistic simulation to be useful. To the best of our knowledge, this is the first root canal access opening simulator.

Beside the VR environment, we have experimented with the possibility of developing an augmented reality (AR) variant of the training system. Students using the AR simulator might benefit from better hand-eye coordination and an environment that is closer to a real clinical setting. We discuss preliminary results of this work in Appendix A.

1.4.2 Automatic Performance Assessment on Dental Process

The second area of contributions of this thesis is related to the development of novel techniques for automatic performance assessment in a VR dental simulator. We have developed algorithms for assessing user behaviors during performance of a procedure (process assessment). The system monitors important features of the procedure and objectively assesses the quality of the performed procedure using hidden Markov models (HMMs). We have evaluated the accuracy of this technique with data collected from novice dental students as well as experienced dentists. The experimental results show high accuracy in classifying users into novice and expert categories.

1.4.3 Intelligent Tutoring Feedback and Guidance

The third area of contribution for this dissertation is intelligent tutoring. We have developed various strategies for providing feedback and tutoring hints. We generate and display verbal objective feedback on the process after observing the characteristics of each procedure stage, computing statistical results, and comparing them with those of expert performance. We provide augmented kinematic feedback on force utilization and indirect vision with a mouth mirror. We find that the quality of the generated verbal feedback is comparable with that of human experts, and we also find that augmented kinematic feedback is helpful in increasing overall scores and reducing error. We also introduce various intelligent training techniques taking advantage of the simulated environment with haptic sensations. These techniques have potential to help students in psychomotor learning of dental procedures.

1.5 Collaboration Statement

This dissertation builds upon collaboration with members in our research group. The list of publications in Appendix B gives an overview of people involved. The pronoun *we* is used throughout the dissertation to refer to the group members collaborating in various studies that this dissertation is based on. The following members contributed considerably and deserve specific mention:

Dr. Siriwan Suebnukarn, dental expert and instructor from Thammasat University, provided a great deal of useful guidance in the domain and helped with many human studies on dental students and experts from the School of Dentistry at Thammasat University.

Prabal Khanal helped develop the haptic algorithm for the cylindrical cutting burr in the surface-based crown preparation simulator. The results are presented in his master's thesis entitled *Haptic Feedback Model For Simulation Of Cylindrical Cutting Tools Interacting With Arbitrary 3D Objects*.

Kugamoorthy Gajananan helped implement the data representation and haptic rendering parts of the volume-based root canal access opening simulator. This work is presented in his master's thesis entitled *Haptic Rendering Of Arbitrarily Shaped Cutting Tools Interacting With 3D Volumetric Models With Application To Dental Surgery Simulation*.

1.6 Organization of the Dissertation

The rest of this dissertation is organized as follows. In Chapter 2, we describe in detail the algorithms and techniques used in developing our VR dental simulators. This serves as the foundation for the subsequent works on performance assessment and intelligent tutoring. We also discuss results of evaluations of the graphics and haptic display. In Chapter 3, we provide a validation of the root canal access opening simulator, showing how it reduces procedural errors in the actual procedure in the real environment. Chapter 4 presents algorithms for automatic assessment of surgical process using HMMs. In Chapter 5, we describe tutoring techniques including strategies for providing objective verbal and kinematic feedback, and various techniques for transferring of dental motor skills. We conclude and discuss possible extensions of this dissertation in Chapter 6. Finally, we demonstrate in Appendix A, our latest experiments on augmented reality (AR) in dental training simulation. This could provide an environment more similar to the actual clinical setting.

Chapter 2

Virtual Reality Haptic Dental Training Simulation

Integration of virtual reality (VR) technology and haptic technology has resulted in a number of medical simulators for clinical and surgical training. These simulators are extremely valuable. Since they have no recurring costs, they can reduce training costs for medical schools. They also make it possible to simulate a wide variety of clinical and surgical procedures, maximizing teaching effectiveness. Using such simulators, students can practice surgical procedures repeatedly at their own convenience. These benefits cannot be realized through the use of dental phantom heads or real patients.

A few research groups have developed haptic-enabled VR dental simulators. Luciano (2006) developed PerioSim, which allows trainees to practice diagnosing periodontal diseases. Wang et al. (2003) worked on a simulator that allows probing and cutting a virtual tooth. Kim et al. (2005) developed a dental training system with a multi-modal workbench providing visual, audio, and haptic feedback. Yau et al. (2006) propose a dental training system utilizing material stiffness and spring force function.

Most of these dental simulators are in early or experimental stages. Many of them only provide spherical-shaped cutting burrs which are known to be the simplest representation for collision detection, cutting simulation, and force feedback computation in real time. This greatly limits the realism of the simulation for actual dental surgery, in which many kinds of tools in various shapes and sizes are required. Moreover, little work (Steinberg, Bashook, Drummond, Ashrafi, & Zefran, 2007; Konukseven et al., 2010) has been done to obtain evaluation of the realism of the simulators from dental students and experts or to obtain feedback from these potential users.

This chapter is based on Rhienmora, Haddawy, Dailey, Khanal, & Suebnukarn (2008), Rhienmora, Haddawy, Khanal, Suebnukarn, & Dailey (2010), and a recent submitted manuscript by Gajananan et al. First, we briefly discuss haptic interfaces and their use in VR simulation. We then describe different algorithms and techniques used in developing our two dental simulation systems; one utilizes a surface based approach, and the other takes advantage of a volumetric approach. These simulators serve as the foundation for subsequent work on performance assessment and intelligent tutoring. We also evaluate the realism of each simulator and discuss feedback received from dental students and experts.

2.1 Haptics in Virtual Reality Simulation

The term *haptic* derives from the Greek word *haptikos*, which means *relating to the sense of touch*, or from the verb *haptesthai*, meaning *to contact, to touch*. Haptic perception strongly relies on the forces experienced during touch and movement. Users can feel resistance, surface structures and the realism of virtual models (Robles-De-La-Torre & Hayward, 2001). While haptics is considered to be the earliest sense to develop after birth, touch is the least understood sense compared with other sensory modalities.

Figure 2.1: PHANToM Desktop (left) and PHANToM Omni (right) haptic devices (SensAble Inc.)

After early success in the development of visualization methods for virtual reality, research has moved toward haptics and the development of haptic devices. Haptic or force feedback devices provide a feeling of touch and the properties of virtual objects through a motorized hand-held device linked to them. The device renders force in response to user actions and enables interaction with virtual models in 3D space, incorporating the work of eyes and hands.

There are currently around 30 commercial haptic devices available from around 10 manufacturers. Each device varies in terms of degrees of freedom (DoF), workspace, maximum force, stiffness, and price. The most widely used commercial haptic product to date is the PHANToM series from SensAble Technologies, especially its PHANToM Omni and Desktop products (Figure 2.1) (Coles, Meglan, & John, 2010). These two models provide six DoF for positional sensing $(x, y, z, pitch, yaw, roll)$ and three DoF for force feedback (f_x, f_y, f_z). This is sufficient for many simulation tasks. The Omni model is widely used in medical and dental simulation research as it is cost-effective, also making dual configurations possible. The Desktop model provides more precise input sensing and higher fidelity force feedback, but also costs around five times as much. There are products that provide even higher degrees of force feedback but their prices are prohibitively expensive, making them impractical for use on a large scale in medical or dental training schools (Coles et al., 2010).

With the introduction of these haptic devices in VR surgical simulators, surgeons can now touch and feel virtual objects such as human organs and perform virtual operations such as cutting soft or hard tissue with realistic force feedback. However, the realism of a surgical simulation depends critically on the force feedback approach used by the simulator. The problem is difficult, not just a straightforward application of the principles of physics, because of the strict real time requirements and the physical limitations of haptic devices.

2.2 Surface-Based Crown Preparation Simulation

We have developed a VR simulator with haptic feedback allowing dental students to practice dental surgical skills in the context of a crown preparation procedure. Crown preparation is the early step

Figure 2.2: Outcome of a crown preparation on the labial and incisal surfaces of a tooth.

in dental restoration with a crown. After preparation, the dentist makes a dental impression then fabricates the crown. Prior to making the impression, the tooth must be cut with dental burrs to make space for the planned restorative materials.

In this study, the system simulates only labial and incisal preparations in order to avoid conflating tool skills with indirect vision skills requiring a dental mirror. Figure 2.2 shows an example of a desired preparation outcome.

We represent tooth data as a 3D multi-resolution surface model reconstructed from a patient's CT data. We extended the collision detection algorithm presented by Wang et al. (2003) to handle non-spherical tools such as a cylindrical tool. We utilize a vertex displacement technique to simulate tooth cutting with a cylindrical burr. Finally, we conducted a formal evaluation of the simulator's realism and accuracy with a group of dental students and experts.

2.2.1 System Architecture

The simulation system runs on a HP Pavilion dv5000 laptop with a 1.6 GHz Intel processor and 2 GB of main memory. The system's graphics card is the nVIDIA GeForce Go 7400 with 256 MB of video memory. We use a PHANToM Omni haptic device (Figure 2.1) that allows six degrees of freedom for position sensing and generates three degrees of freedom for force feedback. The virtual dental handpiece is locked to the position and orientation of the haptic stylus. We developed the simulator software using C++, OpenGL, the Optimized Collision Detection (OPCODE) library (Terdiman, 2001), and the OpenHaptics SDK 2.0 (HDAPI) (Itkowitz, Handley, & Zhu, 2005).

The simulation system is composed of several components as illustrated in Figure 2.3. The simulator contains two separate loops running in separate threads, a haptic loop and graphics loop, running at different frequencies. The graphics loop runs at around 30 Hz for on-screen animations to appear continuous, while the haptic loop runs at a minimum frequency of 1 KHz to ensure a force feedback latency of at most 1 millisecond, satisfying continuous haptic display. We use a surface model to graphically represent the tooth and the tool. Collision detection and the tooth cutting simulation run within the haptic loop. This is possible due to the OPCODE fast collision detection library and the computational efficiency of the vertex displacement algorithm.

Some data must be shared by the graphics and haptic threads. In order to access and manipulate this

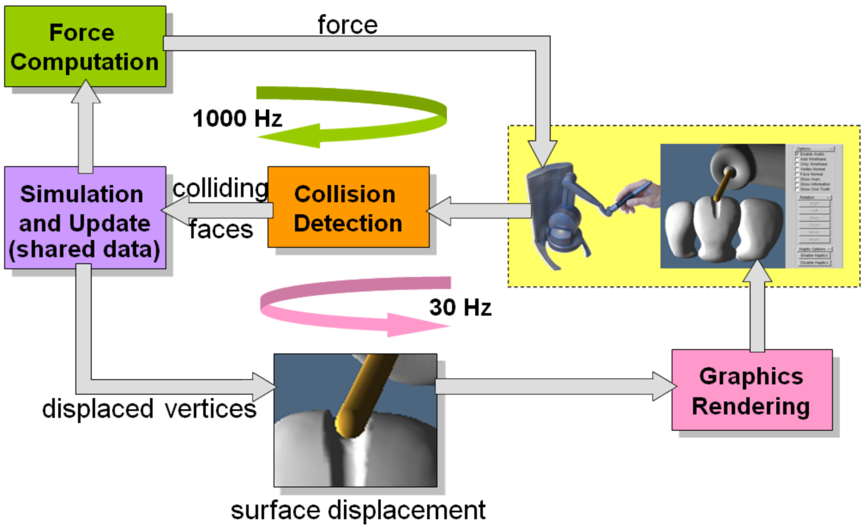


Figure 2.3: Simulator system architecture. A 1000 Hz haptic rendering thread coordinates with a 30 Hz graphics rendering thread to update a 3D surface mesh.

data, the threads need to be synchronized with each other to prevent an inconsistent state. However, the haptic thread, which runs at a higher frequency, should not wait too long for the much slower graphics thread to finish its rendering task. This problem is solved by making fast synchronous calls from the graphics thread that block the haptic thread temporarily and create a snapshot copy of the shared data for graphics rendering.

The graphical user interface (GUI) of our simulator is illustrated in Figure 2.4. It consists of a workspace for the dental operation and a control panel that can be activated by a mouse or keyboard shortcuts. The current position and force feedback of the virtual tool are displayed near the bottom of the interface along with the current percentage of the tooth volume that has been removed.

2.2.2 Data Acquisition and Representation

Volumetric tooth data were acquired from a volunteer (a 23-year-old male) who underwent orthodontic treatment and gave written consent in accordance with the Thammasat University institutional review board prior to the study. The data were obtained from an i-CAT Cone Beam Computed Tomography (CBCT) machine (Imaging Sciences International, PA, USA) covering the whole maxilla and mandible. We processed the volumetric data using three-dimensional volume visualization and segmentation software developed by our group (Suebnukarn, Haddawy, Dailey, & Cao, 2008). The software allows interactive filtering and segmentation.

CBCT volumetric data can be visualized by extracting isosurfaces (surfaces of equal density value) from the volumetric density data and rendering those surfaces as polygonal meshes, or by rendering the volume directly as a block of data (direct volume rendering). The advantage of the surface extraction method over the direct volume rendering method is that it is computationally inexpensive and appropriate for real-time rendering and editing, though it is slightly less realistic than the volumetric method. The marching cubes algorithm (Lorensen & Cline, 1987) is a common technique for

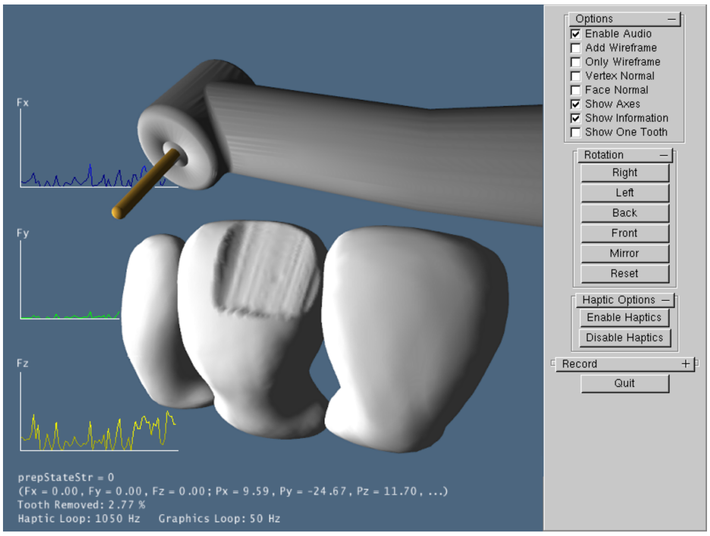
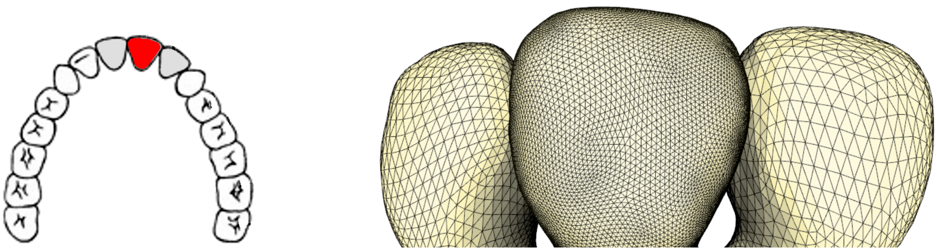


Figure 2.4: Graphical user interface of the crown preparation simulator.



(a) (b)

Figure 2.5: Three teeth (filled) used in the crown preparation simulator (a) and a wireframe representation (b) (Note the finer resolution of the middle tooth.)

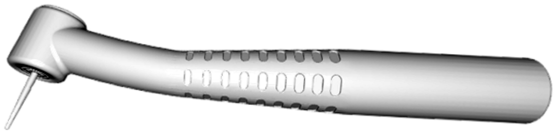
extracting an isosurface from volumetric data.

We construct a surface mesh from the segmented volumetric teeth output of the segmentation tool using the marching cubes algorithm. We currently choose three maxillaries (upper teeth, shown as opaque in Figure 2.5a) as the model for tooth preparation.

The left maxillary central incisor (tooth No. 21, according to FDI World Dental Federation Two-Digit Notation, eighth from the right in Figure 2.5a) is the main tooth used in the tooth preparation simulation. The surface mesh of this particular tooth is further subdivided using a subdivision algorithm (Loop, 1987). The final number of triangles for this mesh is 38,270 (Figure 2.5b).

Much of the previous work on VR dental simulation (Wang et al., 2003; L. Kim et al., 2005; Yau et al., 2006) uses overly simplistic virtual dental tools. To increase realism in our virtual environment, we generated a three dimensional surface model of a dental handpiece with three different burrs (see Figure 2.6 for one example). However, the only burr evaluated in this study is the cylindrical shape.

(a)



(b)

Figure 2.6: Real and virtual handpieces. (a) Photo of a real dental handpiece used in tooth preparation (Twin Power Turbine P, J.Morita Corp.) (b) Our virtual handpiece model.

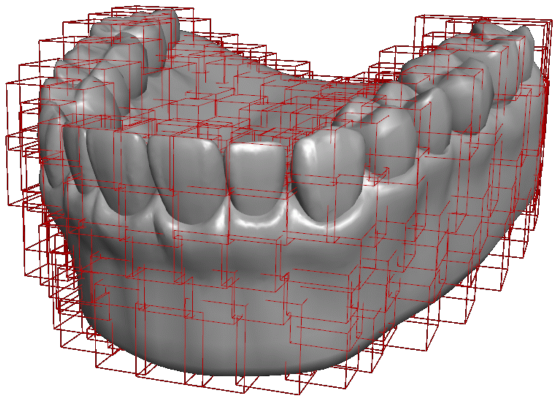


Figure 2.7: An AABB tree visualization of a tooth surface mesh.

2.2.3 Collision Detection

We use a bounding volume hierarchy (BVH) data structure for collision testing between the tooth and dental burr. BVH is a tree-like structure the root of which contains the whole model and each leaf of which contains a smaller subpart. This structure is efficient because the child nodes do not have to be tested if their parent nodes are not in collision. Different bounding volume shapes can be used, but the most common bounding volume shapes are bounding sphere, axis aligned bounding box (AABB), and oriented bounding box (OBB). We use the AABB implementation in OPCODE[1], an open-source C++ library for fast and reliable collision detection (Figure 2.7).

[1]Available at http://www.codercorner.com/Opcode.htm

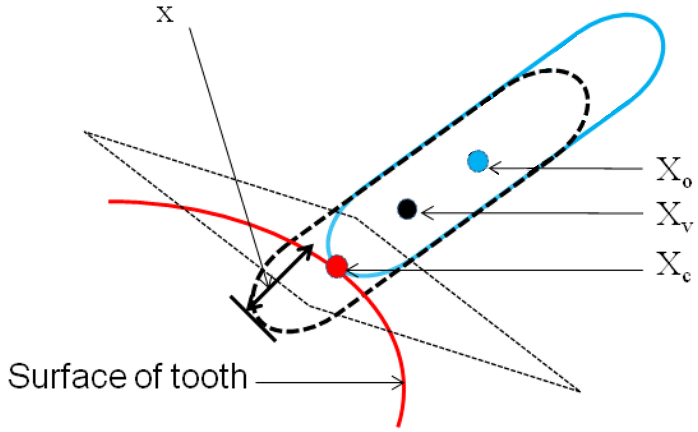


Figure 2.8: Finding the depth of penetration ($\boldsymbol{x}$) of the virtual tool inside the tooth surface.

2.2.4 Haptic Rendering

Force Calculation

When there is a collision between the tool and a tooth, the tool penetrates into the tooth at the area of collision, and the depth of penetration determines the force feedback. When we detect this penetration, we must compute the forces to be rendered by the haptic device in the direction opposite to the movement of the tool, in order to avoid further penetration. The reaction force is directly linearly proportional to the depth of penetration as shown in Equation 2.1:

$$\boldsymbol{F} = k\boldsymbol{x}, \tag{2.1}$$

where $\boldsymbol{F}$ is the 3D force vector calculated at the contact surface, k is a stiffness constant that determines the perceived hardness of the tooth surface, and $\boldsymbol{x}$ is the maximum depth of penetration from the surface of the tooth to the immersed position of the tool inside the tooth surface.

To calculate $\boldsymbol{x}$, we adapt Wang et al.'s (2003) method for spherical tools to the case of a cylindrical tool. We first find contact points on the surface of the tooth. When the tool is in contact with the tooth surface for the first time, an initial virtual proxy position (the position of the tool at first contact) ($\boldsymbol{X}_o$) is stored. On subsequent iterations, as the tool penetrates the surface of the tooth, the new actual position of the tool is recorded as $\boldsymbol{X}_v$. The immersion depth is the distance from $\boldsymbol{X}_o$ to $\boldsymbol{X}_v$ (Figure 2.8). So long as the tool's actual position penetrates the surface of the tooth, we push it back toward the surface of the tooth along the direction of the surface normal at the contact point ($\boldsymbol{X}_c$) until the tool is no longer in contact. Let the displaced position of the virtual tool be $\boldsymbol{X}_s$. Finally the displacement vector is calculated as:

$$\boldsymbol{x} = \boldsymbol{X}_c - \boldsymbol{X}_s. \tag{2.2}$$

Force Filtering

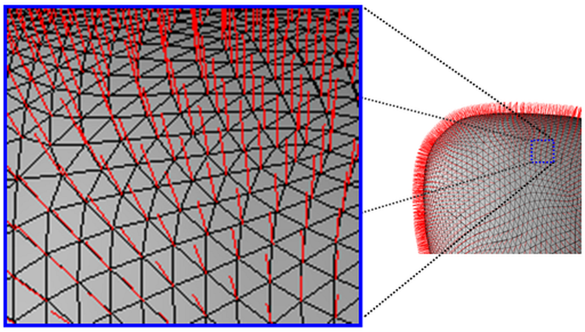


Figure 2.9: Vertex normals of the tooth surface mesh

Due to the effect of averaging normals for each vertex in the penetration volume as well as calculating the center point of the contact surface, the force $\boldsymbol{F}$ will not vary smoothly over time. This is undesirable because, in reality, haptic force tends to be smooth and continuous. To alleviate the problem, following Wang et al. (2003), we limit the change in force between two consecutive intervals:

$$\boldsymbol{F'}_k = \begin{cases} \boldsymbol{F}_{k-1} + \frac{\delta \Delta \boldsymbol{F}}{\|\Delta \boldsymbol{F}\|} & \|\Delta \boldsymbol{F}\| > \delta \\ \boldsymbol{F}_k & \|\Delta \boldsymbol{F}\| \leq \delta, \end{cases} \tag{2.3}$$

where $\boldsymbol{F'}_k$ is the filtered force, $\boldsymbol{F}_k$ and $\boldsymbol{F}_{k-1}$ are forces calculated in two consecutive instances, δ is the threshold value for force change, and $\Delta \boldsymbol{F}$ is $\boldsymbol{F}_k - \boldsymbol{F}_{k-1}$

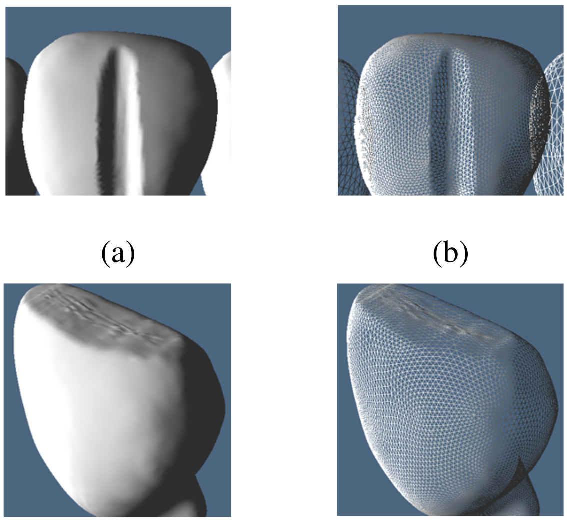
After filtering the force, as described, there is still the possibility of obtaining an overly large magnitude of $\boldsymbol{F'}_k$, which might exceed the maximum force that the haptic device can render. To avoid that from happening, we clamp the force magnitude at the maximum nominal continuous force for the haptic device.

2.2.5 Tooth Cutting Simulation

To simulate tooth cutting during the crown preparation process, we use a vertex displacement technique. This technique is utilized in many digital sculpting software packages. SharpConstruct (Bishop, 2006) is one example. Wang et al. (2003) also use a similar technique for their tooth cutting simulation.

The cutting simulation starts when a collision between the tooth and the tool is detected while a button on the haptic stylus is pressed. Only tooth mesh vertices within the collision area are displaced. For each colliding vertex, we compute the distance from the vertex to the tool in the direction of the vertex normal (Figure 2.9), and then we displace the vertex by the computed distance. Note that the displacement need not be in the direction of the shortest distance between the vertex and the tool.

With this technique, neither the number of triangle faces and vertices nor the structure of the mesh can change. This is a simple approach to cutting simulation that yields acceptable results, as shown



(a) (b) (c) (d)

Figure 2.10: Example results of surface displacement method for tooth cutting simulation. (a) Tooth cutting at the labial surface. (b) Wireframe representation of the cut tooth of (a). (c) Tooth cutting at the incisal surface. (d) Wireframe representation of the cut tooth from (c).

in Figure 2.10.

2.2.6 Experimental Evaluation

Face Validity

Simulations that appear reasonable to experienced users are said to have *face validity*. There are a number of previous face validation studies of the medical VR simulators (Seixas-Mikelus et al., 2010; Kenney, Wszolek, Gould, Libertino, & Moinzadeh, 2009; Ayodeji, Schijven, Jakimowicz, & Greve, 2007; Verdaasdonk, Stassen, Monteny, & Dankelman, 2006), however, the same study for VR dental simulation is still limited (Steinberg et al., 2007). We conducted an experiment to determine the face validity of the VR crown preparation simulator. The face validity of our simulator was evaluated by dental students from the School of Dentistry at Thammasat University. Five sixth-year dental students participated in the evaluation; three were female and two were male.

The study was divided into three sub-sessions. There was a practice session to familiarize the participants with the haptic device and the simulator as a whole. In the second session, participants were given two minutes to perform an experiment in which they had to perform two operations: explore the tooth surface, and partially execute the crown preparation procedure. Finally, in the evaluation session, they had to answer questions on an evaluation sheet. The questions were determined in consultation with a dental instructor and related to the operations the participants had performed during the experimental session. There were three sets of questions: general questions, questions related to exploring the tooth surface, and questions related to the crown preparation operation. Each participant was asked to specify the degree to which he or she agreed or disagreed with each question on a five-level Likert scale (1: Strongly disagree; 2: Disagree; 3: Neither agree nor disagree; 4: Agree; 5: Strongly agree). Participants were also given the opportunity to express their opinions regarding the simulator in a free response format.

The results of this evaluation study as shown in Table 2.1 indicate acceptance and thus face validity of the VR crown preparation simulator among potential users. Various conclusions can be made from the feedback about the realism of the system:

Tooth surface exploration: Three evaluators thought that the tooth surface felt *almost real*, whereas two suggested that the surface hardness and roughness could be improved.

Tooth cutting for preparation: The force required while cutting the tooth was *almost real*, but the evaluators experienced inconsistent force responses while cutting. We found that each participant might be more or less sensitive to response force than others, especially when the amount of force is relatively small.

Graphical user interface (GUI) and ease of use: Some evaluators found it difficult to navigate and control the tool in the simulator. They added that the practice session should have been longer. Moreover, they found that pressing the device's button by hand is not a natural way to start cutting, as real dental chairs provide a foot switch for the task.

Feasibility of the simulator as a training system: Most of the evaluators were positive about the feasibility of using the simulator to teach the use of dental tools. They also added that the simulator could be useful to supplement the material provided in regular classes and that the simulator would be useful for practicing crown preparation.

Construct Validity

To demonstrate *construct validity*, we test the ability of the simulator to produce outcomes that reflect operator skill. We recruited five students and five experienced dentists who had been familiar with our simulator to perform partial crown preparation with the simulator. Ten simulated outcomes completed by them were shown to another expert who was not involved in the experiment to assign outcome scores based on errors found in the incisal, labial-incisal, labial-gingival, and marginal regions of the tooth. Examples of partial crown preparation outcomes are shown in Figure 2.11. The maximum outcome score was 16. Figure 2.12 shows that the experts' mean score (14.4) was significantly different from the novices' mean score (8.4; $p < 0.05$). This result indicates that the simulator captures the important aspects of the differences between novices and experts and hence demonstrates the simulator's construct validity.

2.2.7 Discussion

According to some participants, the feeling of the tooth surface was too rough in some situations. This problem occurred due to discontinuities in the magnitude of the depth of penetration. We subsequently addressed this problem by applying filtering methods to reduce the difference between the depths of penetrations at two different points on the surface. This improved the result to a great extent, but

Table 2.1: Realism evaluation results.

Rating category	N	Mean	Std. dev.
General Questions			
Was the simulator easy to use?	5	2.60	0.55
Do you think that the simulator will be useful in teaching how to use a dental tool?	5	4.20	0.45
Do you think that the simulator can be useful to supplement the material provided in the regular class lectures and demonstrations?	5	4.20	0.45
Was the short amount of time that you were engaged with the simulator sufficient to evaluate its effectiveness?	5	2.60	0.89
Do you think that the simulator took too much time to learn to use?	5	3.40	1.52
Was the simulator useful in helping you to feel the tooth surface when using the virtual tool?	5	3.80	1.10
Exploring the tooth surface			
The tooth surface felt real while touching with the virtual tool	5	3.20	1.10
The surface of the virtual tooth was harder than a real tooth	5	2.60	1.52
The surface of the virtual tooth was softer than a real tooth	5	2.80	0.84
The roughness of the virtual tooth surface was realistic	5	3.20	0.45
The tool often penetrated the tooth surface	5	2.20	0.84
Cutting the tooth			
The force required was higher than expected while cutting	5	3.00	1.22
It took longer to cut than it should actually have	5	4.20	0.84
Did the tool penetrated tooth surface while cutting?	5	4.40	0.55
Do you think this simulator will be helpful to practice dental cutting?	5	4.40	0.89

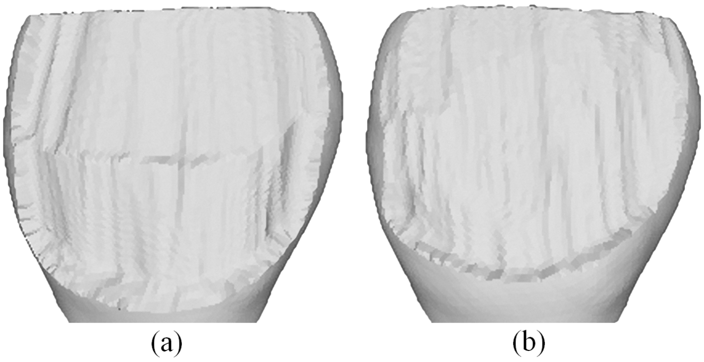


Figure 2.11: Example of two outcomes of crown preparation on the labial and incisal surfaces. (a) An expert outcome. (b) A novice outcome. The novice outcome contains preparation errors on labial surfaces.

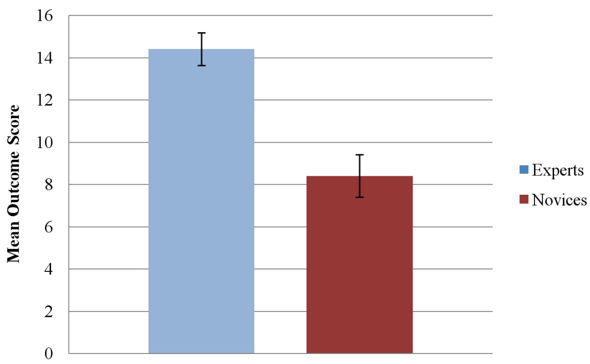


Figure 2.12: Mean outcome scores together with 95% confidence intervals for simulated crown preparation performed by experts (mean = 14.4, SD=0.89) and novices (mean = 8.4, SD=1.14).

it still needs to be improved. The force shading algorithm (Morgenbesser & Srinivasan, 1996) and its variants are interesting topics for future research. For better perception of surface roughness, we might look into a technique to haptically display fine surface textures (Otaduy & Lin, 2004). Moreover, we could improve our force computation algorithm to handle friction on the tooth surface.

A few participants had trouble navigating in the virtual environment. This might have resulted from the lack of depth perception in our two dimensional display. We subsequently added a three-dimensional stereoscopic feature with shutter glasses to the simulator and let those participants try the new interface; the result was positive. We also added a foot switch to replace the button on the haptic stylus for activating the dental drill; this allows operators to hold the haptic stylus in a more natural way. We again let dentists try this new user interface and the outcome was very positive.

The techniques and algorithms presented in this section are for crown preparation only. Other complex dental operations involve complicated factors such as cutting through different layers of a tooth, which have different tissue properties, and the need for other dental tools beside a dental drill. This simulator would have some difficulty simulating operations that involve different tissue types with the vertex displacement algorithm. In the next section, we describe a volumetric approach to represent the tooth and a robust cutting simulation technique that works well with complex dental operations.

2.3 Volumetric Dental Simulation

Existing VR-haptic surgery simulators use a variety of approaches to achieve realistic force feedback. The crown preparation simulator developed earlier uses the geometric surface representation of 3D volumetric models for the force feedback computation. With its vertex displacement technique for tooth cutting, neither the number of triangle faces and vertices nor the structure of the mesh can change. This approach becomes impractical when the volumetric data needs to be permanently removed in real time. The reason is that when material is removed, the contact area changes rapidly, creating discontinuities in the rendered force and unstable haptics.

Volumetric haptic rendering is a technique potentially able to alleviate these discontinuities and instabilities during real time modification of the volumetric data. Volumetric methods compute force feedback as a function of local interactions between voxels in the 3D model and voxels or the surface of the tool.

Most of the systems that implement real time modification of volumetric data only provide a spherical tool, to reduce the complexity of the force feedback computation (Eriksson, Dixon, & Wikander, 2006). For example, Kim et al. (2005) propose a dental training system with a multi-modal workbench providing visual, audio, and haptic feedback that uses a volumetric haptic approach for force feedback. Although the system provides realistic simulation of dental probing and cutting procedures, only a sphere-shaped tool is allowed.

Yau et al. (2006) present an approach for dental procedure simulation that represents the tooth model with an adaptive octree data structure. They implement a variety of different tool shapes, but they use implicit functions to represent the tools. This limits the possible shapes of the virtual dental tools.

McNeely, Puterbaugh, and Troy (1999) demonstrate a volumetric approach using an octree for the 3D data that provides for interaction with arbitrary-shape tools, but they represent the tool with sample points only on the surface. Petersik et al. (2002) also represent the tool model with a cloud of surface sample points in their algorithm for haptic volume interaction with anatomic models. Similarly, Yau and Hsu (2006) present a dental simulator that uses surface point samples to implement the interaction between different shapes of dental tools and tooth model. According to Morris et al. (2006), approaches that only sample surface points from the tool require complex and time-consuming ray tracing computations. These approaches can also lead to unrealistic cutting simulations and uneven material removal.

We introduce a new method for force feedback computation in surgical simulations with volumetric models that addresses some of the limitations of existing work. The method allows for a variety of different surgical tool shapes and real time modification of the volumetric data. To represent tools, we use a volumetric sampling approach that is computationally efficient yet provides for realistic, stable cutting simulations and even removal of material.

Our method uses a hybrid data structure similar to that of Morris et al. (2006), who maintain a dynamic volumetric voxel density array for haptic rendering as well as a triangular surface mesh for graphic rendering. We extend Morris et al.'s approach to allow for non-spherical tools, and we improve upon the efficiency of their surface reconstruction algorithm by using efficient isosurface mesh generation techniques.

Although a primary objective of this work is to develop a dental training simulator, our techniques are completely general. The 3D volumetric models could be any solid objects composed of varying densities.

After presenting our system and haptic rendering algorithms, to verify how well the new haptic feedback algorithm supports realistic simulation of dental procedures with different tools, we report on a systematic evaluation of the system with a group of dental students and expert dentists performing a root canal access opening procedure. The evaluation shows that the force feedback algorithm and resulting simulator provides good to very good levels of realism and very good to excellent levels of usefulness for dental training.

2.3.1 System Architecture

Our volumetric dental simulator consists of a graphical display and a haptic device for simulation of a variety of different virtual dental tools. The system allows for two main modes of interaction, probing and cutting. Probing allows the dentist to practice using a probe to examine the surface of a tooth, to feel its hardness, and to determine the location of carious lesions (soft tissue). Cutting allows the dentist to practice drilling and cutting a tooth in preparation for a variety of dental procedures.

Figure 2.13 shows the architecture of the simulator schematically. A user of the virtual environment operates the haptic device's stylus while the haptic device's sensors report the stylus' position and orientation. If the virtual representation of the haptic stylus (bur) collides with other virtual objects, the system computes and renders force feedback; otherwise, the haptic device remains passive. The 1000 Hz haptic rendering thread is synchronized with a 30 Hz graphics rendering thread. The graphics thread maintains the 3D volumetric model of the tooth, and it updates the corresponding triangular

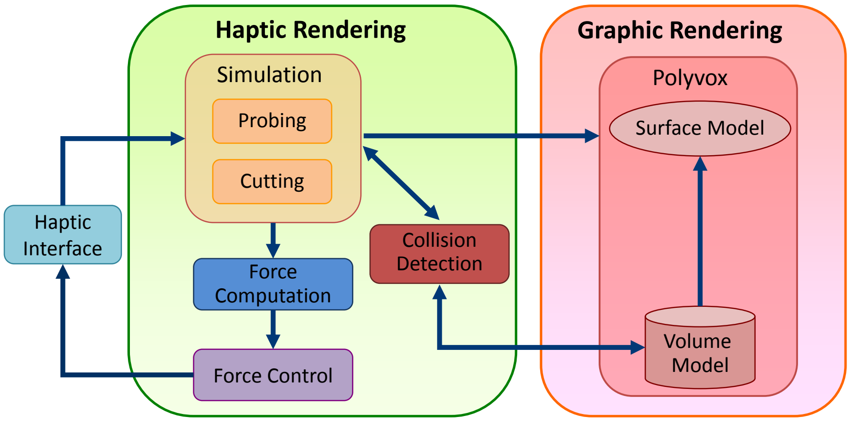


Figure 2.13: Simulator system architecture. A 1000 Hz haptic rendering thread coordinates with a 30 Hz graphics rendering thread to update a 3D volumetric model and a corresponding triangular surface mesh.

surface mesh as the volumetric data is modified during cutting operations.

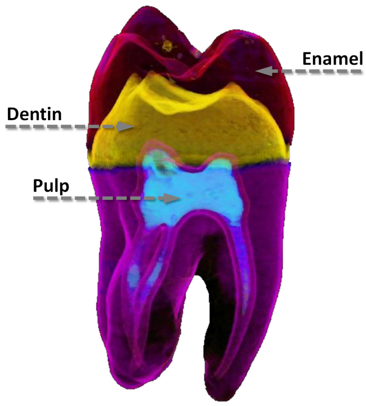
We built the simulator on a standard PC with an Intel Core 2 Duo 2.8 GHz CPU, 4 GB RAM, and an nVidia GeForce 9600GT 512MB. Our haptic device is the Sensable Phantom Desktop, a six-degree of freedom pointing device with three degrees of freedom for force rendering. We use the Microsoft Visual Studio 2005 IDE for Windows XP, the OpenHaptics library (Itkowitz et al., 2005) for communication with the haptic device, and the PolyVox volumetric rendering library for surface mesh extraction (D. Williams, 2010).

2.3.2 Volumetric Data Acquisition and Representation

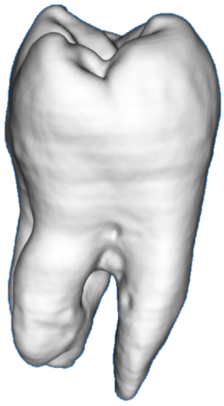
Tooth Model

The simulator requires a model of the anatomical structure to be manipulated in the form of a three dimensional grid of voxels representing the density of the structure at each point with a value between 0 and 255. For example, Figure 2.14a shows a volume rendering of micro scan data for a right maxillary (upper) first molar (tooth number 16) provided by Menz (2006). The volume rendering of the tooth reveals its multi-layer structure with different materials. The outermost material is the very hard *enamel* which covers the tooth surface. The *dentin* layer underlies the enamel is also quite hard. The *pulp* is soft tissue containing nerves as well as blood vessels.

Our system performs visualization, haptic rendering, and real-time modification of the volumetric data with the help of the PolyVox library (D. Williams, 2010). PolyVox is primarily aimed at providing 3D game engines with the ability to interact with “destructible” environments, but it is also readily adaptable to virtual reality and haptic rendering applications. PolyVox implements a hybrid 3D grid and triangular surface mesh data structure similar to that of Morris et al. (2006). The 3D grid is used for haptic rendering and real time modification. The triangular surface mesh model is used for graphic rendering. The surface mesh is extracted as an isosurface of the 3D grid (Figure 2.14b)



(a)



(b)

Figure 2.14: A micro scan of a right maxillary (upper) first molar (tooth number 16) acquired at a voxel resolution of 128 × 128 × 256. a) Volume rendering. b) Isosurface extracted from the tooth volumetric data. Data provided by Menz (2006).

using the marching cubes algorithm (Lorensen & Cline, 1987), and the surface mesh is efficiently updated whenever a change to the 3D grid occurs. The library provides a "BlockVolume" data structure which contains the volumetric data and maps between surface elements (vertices) and volumetric elements (voxels). The PolyVox BlockVolume must have the same number of voxels in the x, y, and z dimensions, so we pad the original 128 × 128 × 256 voxel data to 256 × 256 × 256.

Dental Tools

Our simulator provides dental tools with four different bur shapes:

- Cylinder bur: a flat-ended, cylindrical bur used for cavity preparation.
- Capsule bur: a round-ended, cylindrical bur used for crown preparation.
- Cone bur: a flat-ended, tapered bur used for crown preparation and creating an opening to the pulp.
- Sphere bur: a round bur used for removal of caries (tooth decay).

Our 3D model for each of the four tool shapes is shown in Figure 2.15.

For graphic rendering, we use the surface mesh representation of the entire tool. For haptic rendering, we perform uniform volumetric sampling of a set of points from the bur region of each tool. Collisions with tool regions other than the bur are currently ignored.

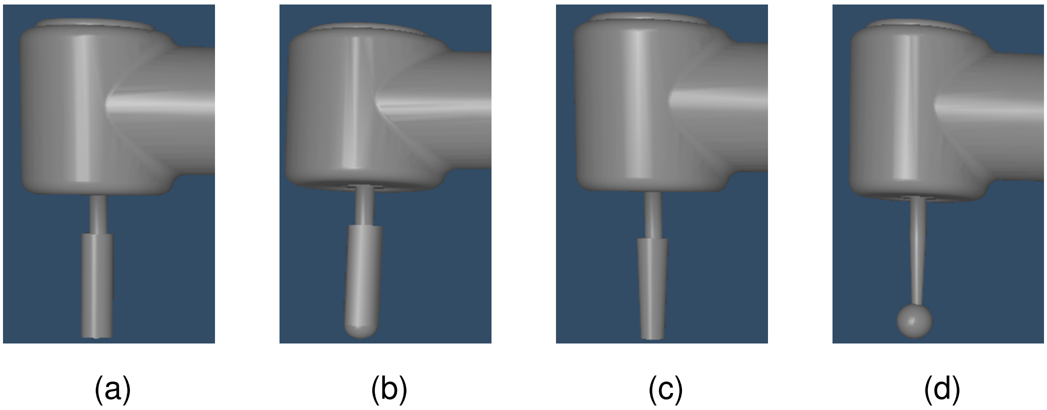


Figure 2.15: Different shapes of cutting tools. a) Cylinder bur. b) Capsule bur. c) Cone bur. d) Sphere bur.

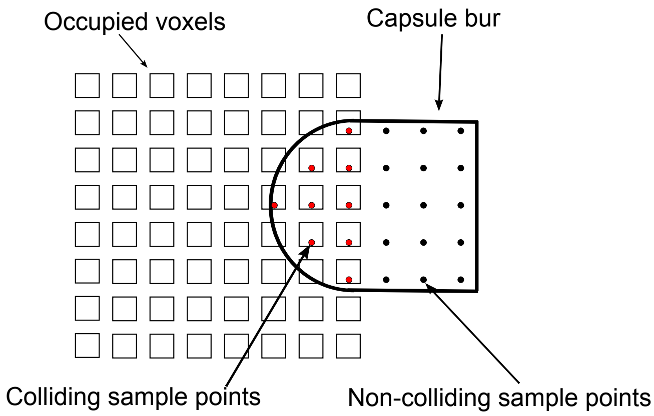


Figure 2.16: Collision detection scenario. A capsule bur tool collides with the occupied region of the volumetric representation of a 3D model. Red sample points are in collision with occupied voxels.

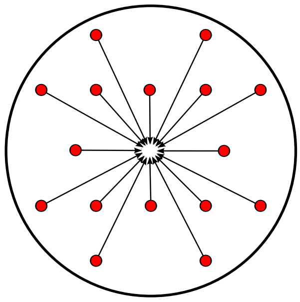


Figure 2.17: Force model for spherical bur tool.

2.3.3 Collision Detection

At system startup time, the simulator loads the volumetric tooth model data (voxel density values) into PolyVox's 3D grid array and volumetrically samples the chosen bur. In each interactive haptic time step, the system checks each volume sample point in the tool for an intersection with the tooth volume. More specifically, the (x, y, z) coordinates of a sample point are first transformed from the tool coordinate system into the tooth model's coordinate system based on the haptic stylus' current position and orientation. Then the coordinates of the point are rounded and mapped to a voxel in the 3D grid. If the position in the grid is occupied (has density greater than 0) then the sample point is said to collide with the tooth model. Figure 2.16 shows an example of a collision of a capsule bur with a set of occupied voxels. The collision detection process is an integer-based constant-time operation that is fast enough to maintain the haptic loop at the rate of 1 kHz on a standard PC.

2.3.4 Force Feedback

Our haptic device provides three degrees of freedom for force feedback. This means that on each iteration of the haptic loop, our simulator must calculate the force to render in the x, y, and z directions. Our method is based on the volumetric sample points from the tool that are, at that particular point in time, immersed in (in collision with) occupied voxels of the 3D model (see Figure 2.16). The direction of the output force vector is based on a summation of force vectors corresponding to individual sample points. The magnitude of the output force vector is based on the number of immersed tool sample points and the average density of the 3D model voxels in collision with the sample points. As either the number of points in collision or the density of the voxels in collision increases, so does the magnitude of the output force.

Computing the individual force vectors for sample points on a spherical bur is the most straightforward. Suppose we have a set of points $\{\boldsymbol{p}_i\}_{i\in 1..N}$ in collision with occupied voxels of the 3D model. The force vector corresponding to sample point i is simply $\boldsymbol{f}_i = \overline{\boldsymbol{p}} - \boldsymbol{p}_i$, where $\overline{\boldsymbol{p}}$ is the center of the bur. See Figure 2.17 for a visualization. When the individual force vectors $\boldsymbol{f}_i$ are summed, we have an aggregate force pushing the center of the bur away from the voxels that are in collision with the bur. The contribution of each individual sample point to the aggregate direction of the force is proportional to its distance from the center of the bur, so that sample points near the surface of the bur get the most weight in the computation.

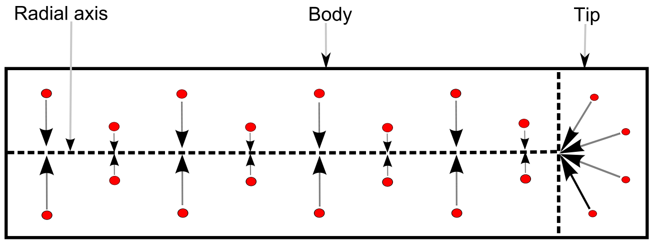


Figure 2.18: Force model for cylinder bur tool.

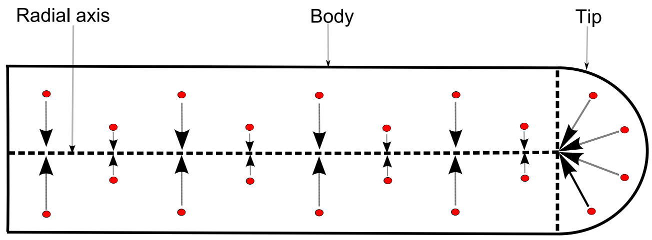


Figure 2.19: Force model for capsule bur tool.

Computing the individual force vectors for sample points on other bur shapes requires a slightly more sophisticated approach to achieve realistic-feeling simulations. For cylinder, capsule, and cone bur tools, we divide the tool shape into two regions: body and tip, as shown in Figs. 2.18, 2.19, and 2.20, respectively. The points in the set of colliding sample points $\{\boldsymbol{p}_i\}_{i\in 1..N}$ are classified by whether they are in the body region or tip region. For points $\boldsymbol{p}_i$ in the tip region, the strategy is similar to that for the spherical bur: the force vector is $\boldsymbol{f}_i = \overline{\boldsymbol{t}} - \boldsymbol{p}_i$, where $\overline{\boldsymbol{t}}$ is the point on the tool's radial axis at which the tip and body meet. For points $\boldsymbol{p}_i$ in the body region, the force vector is $\boldsymbol{f}_i = \mathrm{proj}(\boldsymbol{p}_i, \boldsymbol{r}) - \boldsymbol{p}_i$, where $\mathrm{proj}(\cdot,\cdot)$ is the orthogonal projection operator and $\boldsymbol{r}$ is the 3D line corresponding to the tool's radial axis. Similar to the spherical bur tool, each point's contribution to the aggregate force direction is proportional to its distance from the tool's radial axis or tip center. This structure for the individual force vectors maintains force continuity and provides realistic feedback as a user touches a 3D model with the tip of a tool then rotates the tool to touch the 3D model with the side of the tool.

After computing the individual force vector $\boldsymbol{f}_i$ for each colliding tool sample point $\boldsymbol{p}_i$, we compute a scaled aggregate collision force

$$\boldsymbol{f}_{\mathrm{coll}} = (\overline{d} + c_1 N)\frac{\sum_{i=1}^{N} \boldsymbol{f}_i}{\|\sum_{i=1}^{N} \boldsymbol{f}_i\|}, \tag{2.4}$$

where $\overline{d}$ is the average density of the voxels in collision with the tool, N is the number of tool sample points in collision with the 3D volume, and c_1 is a positive scaling constant, which we determine empirically. The magnitude of the final aggregate force thus increases with the density of the voxels in collision with the tool and the number of tool sample points in collision with the 3D model. Basing the gain calculation on the average voxel density is similar to the method of Kim and Park (2006), and basing it on the number of sample points in collision is similar to the method of Morris et al. (2006).

After computing the collision force $\boldsymbol{f}_{\mathrm{coll}}$ according to Equation 2.4, at time T, we finally add a

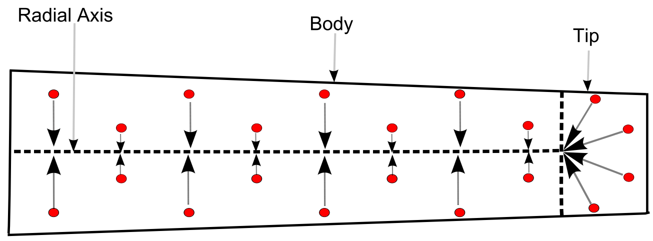


Figure 2.20: Force model for cone bur tool.

dampening force in the direction opposite the haptic device's current trajectory, yielding the raw force feedback vector $\boldsymbol{f}_{\text{raw}}^{(T)}$ for time T:

$$\boldsymbol{f}_{\text{raw}}^{(T)} = \boldsymbol{f}_{\text{coll}} - c_2 \boldsymbol{v}^{(T)}. \tag{2.5}$$

$\boldsymbol{v}^{(T)}$ is the estimated velocity of the haptic stylus at time T, and c_2 is a positive scaling constant, determined experimentally. Note that no dampening force is applied unless $\boldsymbol{f}_{\text{coll}}$ is non-zero, i.e., unless a collision has been detected.

Force Smoothing and Filtering

To reduce vibration effects due to abrupt changes in the direction of the rendered force, we smooth the raw force vectors computed via Equation 2.5 using a simple weighted moving average technique and clamp high-magnitude forces to avoid hardware damage. Similar smoothing approaches to reduce vibration and unstable force feedback are common in haptic applications (Otaduy & Lin, 2006a).

In our scheme, at time T, we first compute a weighted average of the forces previously rendered at each point in time in a K-element history window as follows:

$$\boldsymbol{f}_{\text{hist}}^{(T)} = \frac{\sum_{t=1}^{K} w_t \boldsymbol{f}_{\text{smooth}}^{(T-t)}}{\sum_{t=1}^{K} w_t}.$$

$\boldsymbol{f}_{\text{smooth}}^{(T-t)}$ is the actual rendered force from time $T-t$; for the weights w_t, we use a simple linear weight decay rule to emphasize recently rendered forces more than less-recently rendered forces. Then, we compute the smoothed force

$$\boldsymbol{f}_{\text{smooth}}^{(T)} = H(\boldsymbol{f}_{\text{raw}}^{(T)}, \boldsymbol{f}_{\text{hist}}^{(T)}) \tag{2.6}$$

where $H(\boldsymbol{v}_1, \boldsymbol{v}_2)$ is a vector mean that normalizes its inputs, takes the arithmetic mean of the normalized vectors, then scales the result by the harmonic mean of the original vectors' magnitudes. We arrived at this method after experimenting with several different methods for combining the direction and magnitude of the current and historical force vectors.

Parameter Settings

Our system utilizes several parameters that must be adjusted to obtain realistic-feeling simulation of probing and cutting operations.

The first parameter is the density of the sample points on the tool model. If the sample points are too sparse, we obtain soft, discontinuous force feedback resulting in unrealistic penetration of the tooth model. The problem of discontinuous force feedback due to sudden changes in the number of immersed sample points has also been noticed by other researchers (Tsai, Hsieh, & Tsai, 2007). If the sample points are too dense, the force calculation may take too long to maintain a 1 kHz haptic loop. We find that 1 kHz is the minimum rate for a realistic simulation. For our tools, using around 3000 sample points is sufficient to achieve smooth force rendering without affecting the cycle time of the haptic loop on a commodity PC.

The next parameter is the scaling constant c_1 in Equation 2.4. If c_1 is too small or too large, we obtain surfaces that feel too soft or too stiff. For a fixed tool sample point density, we simply adjust c_1 by trial and error until the surface stiffness is satisfactory.

The dampening force introduced in Equation 2.5 introduces a feeling of viscosity during probing and drilling. Higher values for the scaling constant c_2 increase the feeling of viscosity and also help to reduce vibration, kicking, and buzzing effects due to rapid changes in force direction, but values that are too high make tooth surfaces feel sticky and make drilling unnaturally difficult. As with c_1, we adjust c_2 until the feeling of viscosity is satisfactory.

Our force smoothing scheme (Equation 2.6) requires a window size K and weights w_t. If K is too small, we experience vibration, buzzing, and kicking effects, and if it is too large, we obtain unrealistically soft, spongy surfaces. We find that $K = 100$ with a maximum weight $w_1 = 1.3$, a minimum weight $w_{100} = 1.0$, and linear interpolation in between, provides a suitable tradeoff between stability and responsiveness.

2.3.5 Graphical Rendering

Our graphical rendering scheme uses surface meshes for the tooth, bur, tool handle, and mirror. The surface mesh for the tooth is generated from the volumetric representation of the tooth and must be updated whenever the 3D volumetric data is modified during cutting operations. To make this efficient, we use OpenGL's vertex buffer objects (VBOs). A VBO is an opaque handle to a region of fast RAM, managed by OpenGL, allowing fast transfer of vertex data (points, surface normals, texture map indices, and so on) to the graphical processing unit (GPU) (I. Williams, 2010). OpenGL applications can map VBOs to CPU addresses, read and/or write vertex data in the VBO, then unmap the VBO for rendering by the GPU. We use the *dynamic draw* access mode that allows for an arbitrary pattern of specifying, modifying, and rendering vertex data. The use of VBOs roughly doubles our graphical rendering rate.

We create one VBO for each of a set of regions of the PolyVox BlockVolume. As mentioned earlier, we use a voxel array of size 256 $\times$ 256 $\times$ 256. We partition this grid into regions of size 16 $\times$ 16 $\times$ 16, for a total of 256 regions. Each of these regions is associated with a designated VBO that stores the corresponding set of surface vertices and normals for the surface mesh. We also maintain a *dirty region* array of Boolean flags indicating the regions that have been changed during cutting simulation. The flags in this array are set in the haptic rendering loop as modifications are made to the 3D grid data. On each iteration of the graphic rendering loop, we first use the OpenHaptics toolkit's (Itkowitz et al., 2005) facilities to obtain a thread-safe snapshot of the state. We then request PolyVox to recompute the surface mesh for the dirty regions, map the VBOs for the dirty regions to

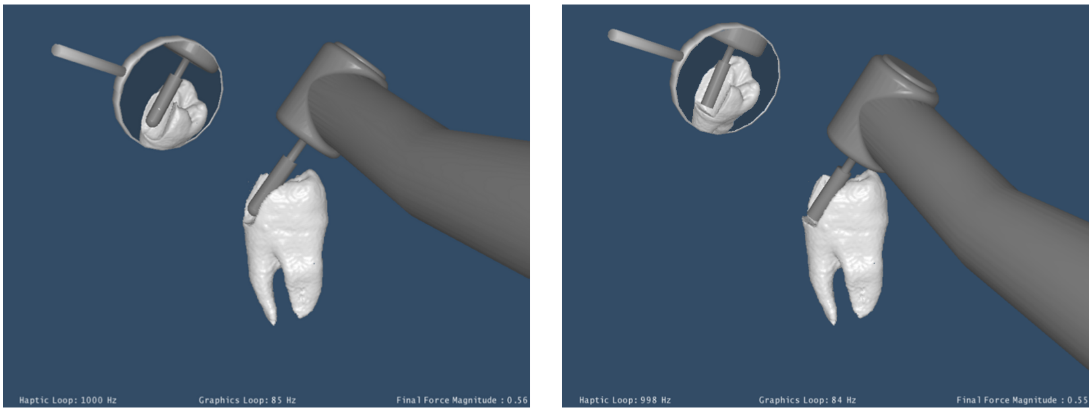
CPU memory, update the VBOs, unmap the mapped VBOs (allowing them to be transferred to the GPU for rendering), then clear the dirty region array.

We also use VBOs for the tool and mirror vertex data to make rendering them more efficient, but since these objects never change during simulation, we simply create the VBOs at system startup time in *static draw* mode and allow OpenGL to manage them for the entire simulation.

2.3.6 Tooth Cutting Simulation

Our simulator is equipped with a foot pedal similar to the pedal dentists use to activate their drill. When the user activates cutting via the foot pedal, on each iteration of the haptic loop, every 3D model voxel in collision with a tool sample point is set to a density of 0, and corresponding regions of the BlockVolume are marked as dirty.

The size of the update depends on the stiffness of the region being cut and the amount of force applied by the user. We find that a 1000 kHz haptic loop and a 30 Hz graphic loop are sufficient for realistic haptic and visual simulation of cutting operations. Figure 2.21 shows screen shots of simulated cutting operations with two different tool shapes.



(a) (b)

Figure 2.21: Snapshots of simulated cutting operations. (a) Cutting with a capsule bur tool. (b) Cutting with a cylinder bur tool.

2.3.7 Experimental Evaluation

Face Validity

The face validity of our access opening simulator was evaluated by dentists and dental students from the Faculty of Dentistry at Thammasat University, Thailand.

Participants

Figure 2.22: An example of access opening outcome showing all four canals clearly.

We recruited two experts with 10 or more years of experience, one experienced dentist with five or more years of experience, and seven novices with less than five years of experience.

Procedure

Each participant participated in a single session consisting of an introduction to the simulator, training on the use of the virtual dental tools, and a test.

The participants' ultimate task was to perform an access opening procedure on the upper right first molar. The access opening is the first step in root canal therapy which involves drilling down to the pulp chamber where the nerve tissue resides. Figure 2.22 shows an example of a desired access opening outcome.

All participants were briefly instructed on the use of the system and the requirements of access opening. They received a verbal explanation about the use of the system from the investigators and familiarized themselves with the system interface, but not with the task, for 15 minutes. During this familiarization or warm-up period, participants were allowed to ask questions and receive further verbal explanation and suggestions from the investigators.

The participants were then requested to perform the following four steps of root canal access opening:

1. Cut into palatal pulp horn.
2. Extend the opening laterally to the mesio-buccal canal orifices.
3. Extend the opening laterally to the disto-buccal canal orifice.
4. Extend the opening laterally to the palatal canal orifice.

After the test session, each participant was given an evaluation form to rate his or her experience with the simulator. Participants were asked to rate the simulator along the following dimensions:

1. The realism of the haptic feedback during tooth probing and cutting operations.

Table 2.2: Haptic rendering evaluation results.

Rating category	N	Mean	Std. dev.
Tooth Anatomy			
Different Stiffness	10	4.40	1.35
Cutting Force	10	4.10	1.45
Cutting Time	10	4.30	1.06
3D Instruments' Realism			
Capsule	10	4.80	1.14
Cylindrical	10	4.80	1.03
Conical	10	4.80	1.03
Spherical	10	4.70	1.06

2. The realism of the graphic visualization of tooth model and dental instruments.
3. The simulator's usefulness and ease of use.

Participants performed a series of ratings on a seven-level Likert scale (1: Very poor; 2: Poor; 3: Fair; 4: Good; 5: Very good; 6: Excellent; 7: Exceptional) for each of the three categories.

Results

Tables 2.2, 2.3, and 2.4 show the mean and standard deviation of the participants' responses in each evaluation category.

As shown in Table 2.2, on average, participants rated the realism of the feeling of the tooth model as "Good" and the realism of the feeling of the dental tools as "Very good." The variance of the responses was relatively high, however; this might reflect the different levels of experience among the participants.

Table 2.3 shows that on average, participants rated the realism of the graphic visualization of the tooth and tools as "Very good," with relatively high variance in the ratings of the visualization of the crown. The participants were on the whole very satisfied with the simulator's graphical rendering.

Table 2.4 shows the evaluation results for usefulness and ease of use. The simulator was rated on average as "Excellent" for learning dental skills and for teaching tooth preparation. As a tool for assessing dental skills, the simulator was rated as "Very good" with relatively high variance that might indicate the novices' lack of experience to judge this factor. The simulator's comfort was rated as "Good" whereas its user interface was rated as "Very good."

Table 2.3: Graphic rendering evaluation results.

Rating category	N	Mean	Std. dev.
Tooth Model Overall Realism			
Crown	10	4.80	1.32
Roots	10	5.20	0.92
Root Canal Orifices	10	5.40	0.84
3D Instruments' Realism			
Capsule	10	5.30	0.82
Cylindrical	10	5.20	0.63
Conical	10	5.10	0.88
Spherical	10	5.10	0.74

Table 2.4: Simulator usefulness and ease of use evaluation results.

Rating category	N	Mean	Std. dev.
Usefulness			
Learning Dental Skills	10	5.60	0.70
Assessing Dental Skills	10	4.90	1.28
Teaching Tooth Preparation	10	5.60	0.52
Ease of use			
Comfortable	10	4.40	1.07
Felt Focused	10	4.60	0.84
Friendly User Interface	10	4.90	0.99

We conclude that the proposed volumetric dental simulator has face validity. The simulator provides sufficiently realistic simulation of dental probing and cutting operations to support virtual dental training and skill assessment.

2.3.8 Discussion

We have demonstrated the feasibility of the approach in a case study application to virtual reality training for dental students that allows for the use of four common dental tool bur shapes: cylinder, capsule, cone, and sphere. In an evaluation of the prototype system by 10 dentists, we find that our haptic feedback method provides sufficiently realistic feeling during probing and cutting operations.

There are numerous directions for improvement and future research. Currently, the densities of 3D model voxels in collision with the tool during cutting are immediately cleared to 0, leading to occasional artifacts in the graphic rendering. This could be improved with more sophisticated material removal techniques. We still face occasional problems with force discontinuities, vibration, unrealistically stiff surfaces, buzzing, and kicking. The filtering and dampening techniques previously discussed dramatically reduce these effects, but further experimentation is required to eliminate them completely.

Some of the challenges we faced could be addressed using six degree of freedom force feedback and realistic simulation of the physics including torque, but the cost of six degree of freedom devices makes them impractical for use on a large scale in medical training schools. Heuristic approaches to haptic feedback in under-actuated devices is thus an important area for future research.

2.4 Summary

We have described haptic interfaces in VR simulation and introduced our surface and volumetric dental simulators. The surface-based system can simulate tooth surface exploration and cutting for crown preparation. Its graphics and haptic rendering are based on a triangle mesh model. Tooth cutting is simulated by displacing the surface mesh, which is computationally inexpensive and works well for crown preparation, but would have difficulties in other more complex procedures. However, the initial evaluation results are promising as dental students agree that the simulator could be very useful in dental skills training. This led us to develop a more sophisticated volume-based dental simulator. The volumetric simulator uses a hybrid volumetric/surface mesh representation of the 3D model. The volumetric representation provides for realistic simulation of probing and cutting operations on anatomical structures having different densities in different locations, and the real-time surface reconstruction allows efficient graphical rendering of the model as it is being modified. The haptic feedback method is based on a volumetric point sampling technique that makes it possible to provide realistic haptic feedback for arbitrary tool shapes. An evaluation shows that the volumetric based simulator provides sufficiently realistic feeling during probing and cutting operations of a complex procedure.

With VR training simulators, every aspect of the operator's work can be recorded during the simulation and analyzed further to provide a fine-grained objective assessment and feedback. Our simulators described in this chapter serve as a foundation for subsequent work on performance assessment and intelligent tutoring.

Chapter 3

Effectiveness of Virtual Reality Simulation in Dental Skill Acquisition

VR simulation has played an introductory role for clinical trainees in medicine and dentistry for almost two decades (Satava, 1993). At the beginning, however, VR training was regarded as a game-like exercise. The robustness of data demonstrating the validity and transferability of skills from VR systems is inferior to that of other training methods (Tsuda, Scott, Doyle, & Jones, 2009). Thus, it is crucial to demonstrate that training with VR simulators actually improves surgical performance in the operating room or similar clinical environments.

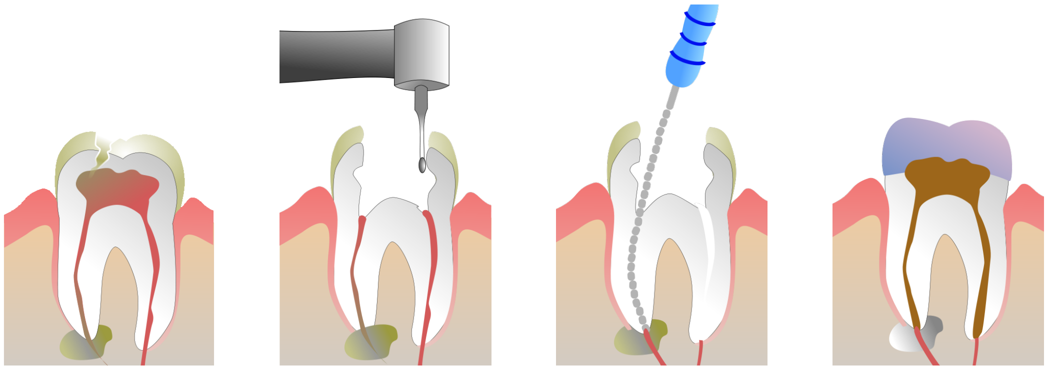
We provided results of a realism evaluation and discussed students' and experts' perception of our VR crown preparation and access opening simulators in Chapter 2. While the promise of our system as a training tool was encouraging, it was still necessary to determine whether it was comparable or superior to conventional training methods in terms of validity and skill transferability.

Dental practitioners need to acquire knowledge and skills in the early stage of training to reduce risk of treatment errors. Root canal access opening, for example, is a procedure associated with unforeseen procedural errors such as perforations, resulting in 30% reduction of success rate in root canal treatment (Barone, Dao, Basrani, Wang, & Friedman, 2010). However, studies and evidence on the effect of dental training methods in preventing treatment errors in the clinical environment are still limited. To the best of our knowledge, a complete validation study on skill transfer of a VR dental simulator where one control group practices on a traditional method and another group practices on a VR training simulator with haptic feedback has not been carried out.

This chapter is based on Suebnukarn, Hataidechadusadee, Suwannasri, Suprasert, Rhienmora, & Haddawy (2011). We aimed to evaluate the effectiveness of the haptic virtual reality training simulator in minimizing procedural errors in endodontic access opening, an important initial step of root canal treatment (Figure 3.1). We assigned dental students into either a group that trained only on the VR simulator with micro computed tomography (micro-CT) teeth, and a control group that trained on traditional extracted teeth. We hypothesized that the post-training performance of the VR group should be comparable to the control group. If borne out, this would justify the incorporation of the VR simulator into skill development programs for endodontic trainees.

3.1 Prior Evidence of Virtual Reality Effectiveness in Surgical Training

Several research groups in many disciplines have started to demonstrate that training in virtual environments actually improved performance in clinical settings. In laparoscopic cholecystectomy, Seymour et al. demonstrated in a randomized, blinded study that trainees on the Minimally Invasive Surgical Trainer-Virtual Reality system (MIST-VR) performed gallbladder dissection faster and made significantly less errors than trainees using the standard programmatic training (Seymour et al., 2002). For the same discipline, Hytlander el al. showed skill transferability from a group of students training on the LapSim system to basic tasks performed on an animal model (Hyltander, Liljegren,



(a) (b) (c) (d)

Figure 3.1: Root canal treatment procedure. (a) Unhealthy tooth. (b) Access opening. (c) Cleaning of canals with endodontic file. (d) Canal filling and crown. (Photos courtesy of Jeremy Kemp)

Rhodin, & Lnroth, 2002). After these preliminary studies, many other studies have objectively compared VR training with current standard laparoscopic skills training, revealing that VR produced skills are as good as or better than those developed through the conventional program (Sturm et al., 2008; Gallagher & Ritter, 2007).

In the dentistry domain, however, validation study of skill transfer from VR to physical environment is limited. There are some initial reports on validity of the DentSim computerized, phantom-based simulator, which show that students practicing with the system perform better than those practicing the traditional training in certain tooth preparation tasks (Maggio, Buchanan, Berthold, & Gottlieb, 2005; Urbankova, Graham, Lichtenthal, & Hadavi, 2005) and that the simulator trained students require less faculty instruction time (Jasinevicius, Landers, Nelson, & Urbankova, 2004). Another related study demonstrated that skills acquired from the VOXEL-MAN virtual apicectomy (root end surgery) transfer to the physical environment (Sternberg et al., 2007). However, this experiment was carried out only on a porcine (pig) cadaver model.

3.2 Virtual Reality Dental Training Effectiveness, Experimental Design

The volumetric teeth models used in this study were acquired from a micro-CT scanner by Yoshida et al. (Yoshida et al., 2011) and made available to us. Micro-CT is a miniaturized version of computerized axial tomography with a resolution of the order of micrometers (Oi, Saka, & Ide, 2004). Micro-CT teeth data can be reconstructed to three-dimensional images from which structural parameters can be derived. Scanning and analyzing of final teeth after operation using micro-CT scanner has been shown to be effective for quantitative evaluation in traditional training on endodontic access opening (Ikram, Patel, Sauro, & Mannocci, 2009), root canal preparation (Peters, Peters, Schönenberger, & Barbakow, 2003), and obturation (Hammad, Qualtrough, & Silikas, 2009).

In this experiment, we conducted a prospective, randomized, controlled and blind trial to test the hypothesis that training with the VR simulator and micro-CT teeth models would result in minimizing procedural errors and reducing excess tooth mass loss in access opening, similar to those achieved from training with natural extracted teeth on phantom head. First, we recruited dental students to undergo a pre-training assessment of access opening skill on extracted teeth. Then we randomly assigned them to either a group that trained only on the VR simulator or a group that kept training only on extracted teeth. Finally, both groups underwent a post-training evaluation on extracted teeth. Figure 3.2 depicts a flowchart of this experiment.

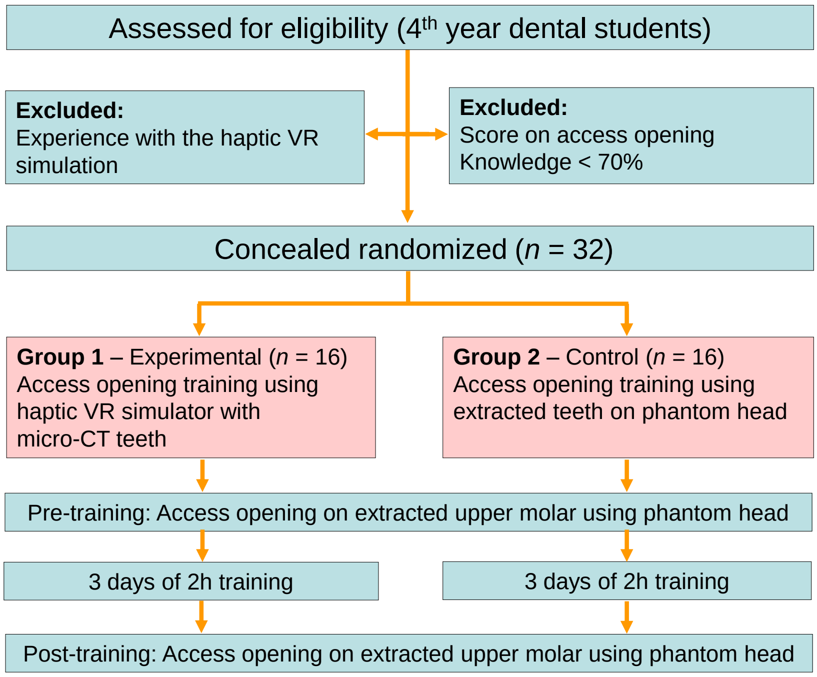


Figure 3.2: Flowchart of the simulator validation study.

3.2.1 Sample Size

Potential dental students beginning their fourth year at the Faculty of Dentistry of Thammasat University were recruited. They were assessed for knowledge in endodontic access opening and had to achieve a score above 70% to participate in the study. None of the participants had previously received any skill training using a haptic virtual reality system. All rated themselves as good or excellent computer users.

We finally recruited 32 dental students; 16 were randomly assigned as experimental participants and 16 as control participants. All participating students gave their written informed consent approved by the institutional Ethical Review Board.

3.2.2 Access Opening with Haptic VR Simulator

Yoshida and colleagues (Yoshida et al., 2011) provided us with 10 radiographic images of extracted human maxillary teeth with dental caries, of which the original patients could not be identified, scanned using their three-dimensional micro-CT (RmCT, Rigaku Co.) under these conditions:

- Resolution of $50 \times 50 \times 50$ μm
- Tube voltage of 90 kV
- Tube current of 150 μA

Then, tomographic images were achieved using i-VIEW dental imaging software (i-VIEW, Morita Co.). Three-dimensional reconstruction was performed using 600 of these two-dimensional images (Figure 3.3).

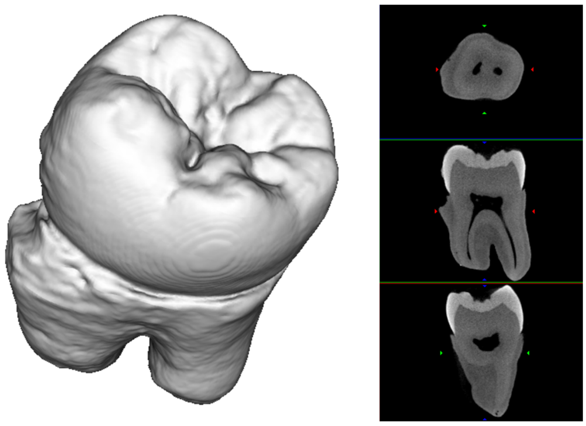


Figure 3.3: An example of reconstructed micro-CT tooth data, provided by Yoshida et al.(2011). The tooth's axial, coronal, and sagittal views are shown on the right (top to bottom).

The VR simulator in this experiment was operated on a standard PC with an Intel Core 2 Duo 2.8 GHz CPU, 4 GB RAM, and an nVidia GeForce 9600GT video card with 512MB of RAM connected to a 15-inch monitor and two PHANToM Omni haptic devices in a dual configuration, representing a handpiece and a dental mouth mirror. The monitor was placed at eye level, and the haptic device was positioned at elbow level directly in front of the participant (Figure 3.4). The methods and algorithms for simulating the access opening procedure is the volumetric approach as explained in Section 2.3 of this dissertation.

The VR participants could view the 3D tooth in various planes prior to cutting and could manipulate the handpiece and mouth mirror using haptic devices. While cutting, they could feel different force feedback when cutting through enamel, dentin, and pulp. During training, the system recorded data associated with the performance process including task completion time, tooth tissue volume loss, force utilization, and handpiece and mouth mirror movements. Playback of the participants' performance in the simulator was provided at the end of each trial, along with information about total tooth volume loss and hand movement patterns. VR participants practiced the procedure with the system two hours a day for three days in one week with no trial limit.

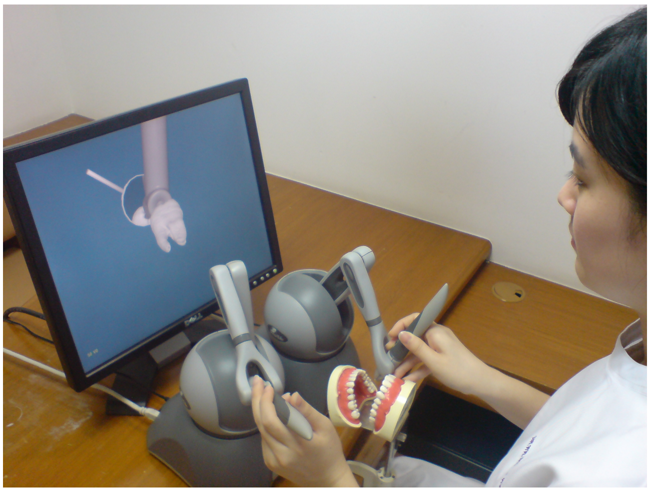


Figure 3.4: A student in the experimental group practicing access opening with the haptic VR simulator.

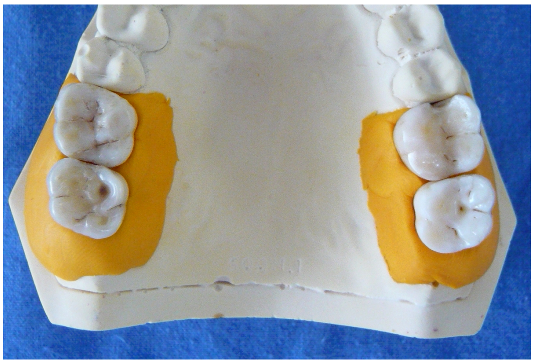


Figure 3.5: Four natural extracted teeth attached to a dentoform with silicone putty for access opening operation on a phantom head.

3.2.3 Access Opening with Phantom Head

Two hundred maxillary molars were selected from a pool of extracted teeth and stored in 0.1% thymol solution until used. All teeth were intact or had at most one surface lesion penetrating to the pulp chamber. Teeth with pulp chambers compromised by calcification or sclerosis were excluded.

Initial preparation of the teeth involved removal of any surface debris and calculus by an ultrasonic scaler (Piezon Master 400, Electro Medical Systems S.A.). The carious lesion was excavated with a slow speed handpiece and steel rose head bur (size 7 REF 100-3223, Henry Schein Inc.), and restored with glass ionomer cement (GIC) (Fuji IX, GC Corp.). All teeth were blotted for 10 minutes on absorbent paper towels and then were weighted on a digital analytical balance with 0.0001 grams accuracy (Analytical balance, Model SI 124; BDH, London, UK), before and after performing access preparation. Prior to the operation, each tooth was held with vinyl polysiloxane putty and attached to the dentoform (Figure 3.5) connected to the phantom head.

The access opening for the control group was performed using a bur diameter of 1.5 mm and a length

Figure 3.6: A student in the control group practicing access opening with a phantom head.

of 3 mm in a high speed handpiece with water coolant. Feedback on outcome was provided by a qualified endodontic laboratory instructor at the end of each trial of three days of two hours training within a week (Figure 3.6).

3.2.4 Outcome Measures

Students from both groups underwent post-training evaluation on extracted teeth. The main outcome measure was procedural errors assessed by an expert blinded to trainee and training status. The secondary outcome measures were tooth mass loss and task completion time. Procedural errors in four walls (buccal, lingual, mesial, distal) and pulpal floor were evaluated and rated on the scale of 0 (best) to 3 (worst). The explanation of each rating is as follows:

0 : Minimally extended cavity affording unimpeded access to and visibility of the orifices of all canals.

1 : A cavity permitting effective debridement of the canal system without prejudice to subsequent restoration.

2 : Incomplete removal of pulp chamber roof and/or inadequate retention form for the maintenance of an effective dressing.

3 : Unidentified canals and/or perforation.

Thus, the total error score over all four walls and one floor could range from 0 to 15; lower scores are better. The mass of each tooth was measured on a digital analytical balance before and after post-training evaluation. The percentage of mass removed for each tooth was calculated and the total time taken to complete the task was recorded.

3.2.5 Statistical Analyses

We used the Wilcoxon matched pairs test to examine the differences between pre-training and post-training error scores of the same group. We used the Mann-Whitney test for unmatched data to detect any differences between haptic VR training and phantom head training groups. Independent t-tests were used to compare the tooth mass removed and task completion time between the haptic VR trained and phantom head trained groups. Statistical significance was defined as a p-value less than 0.05. All analyses were done using SPSS software (SPSS Inc.).

3.3 Results

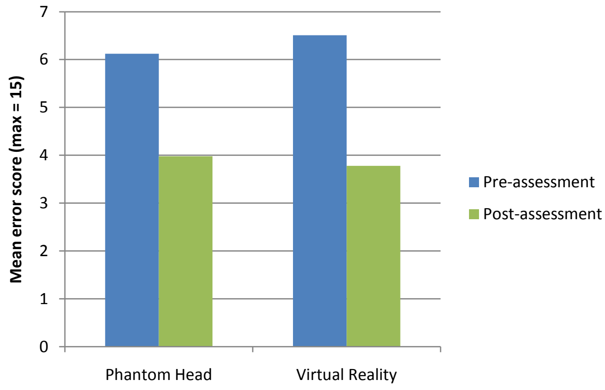
All participants from both groups completed the post-training assessment. There were no significant differences between the groups in the average error scores, tooth mass removed, or task completion time before training. Error scores improved in post-training performance for both the phantom head group (from 6.12 ± 1.35 to 3.98 ± 1.41) and the VR group (from 6.51 ± 2.01 to 3.78 ± 1.10). However, error score reduction between the VR simulator and the conventional training group were not different statistically (Figure 3.7). The VR group significantly decreased the amount of hard tissue volume lost post-training, while there was no significant difference for the phantom head group. There was no significant improvement in task completion time for either group.

3.4 Discussion

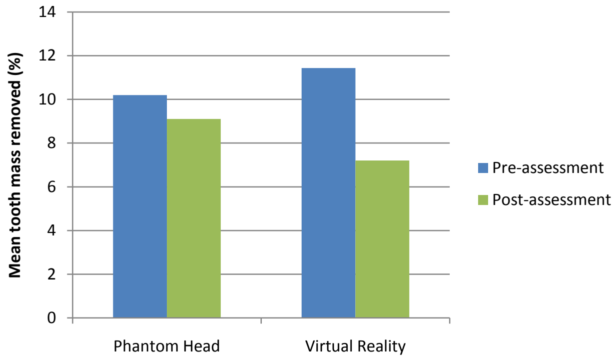
VR simulation allows the use of multi-modality images and instrumentation that is close to the real clinical setting; this is beneficial in clinical education. VR simulators are already recognized by researchers in many disciplines as valuable adjuncts for surgical training outside the operating room (Gallagher & Ritter, 2007). Few studies have shown potential benefits from dental training in the presence of force feedback with VR simulators (Thomas, Johnson, Dow, & Stanford, 2001; Steinberg et al., 2007). However, a potential pitfall of VR simulation is that learners become expert at using simulators but not in the clinical contexts that the simulators are intended to mimic (Kneebone, Nestel, Vincent, & Darzi, 2007). Therefore, it is essential to investigate whether the skills acquired on a simulator actually result in improved skills in clinical settings. We designed the validation study to demonstrate preliminary results to this research question in the environment closed to the operating room. We chose the access opening task as we had shown previously that our VR simulator can realistically replicate the procedure.

Interesting results were obtained regarding the percentage of tooth mass removed. The control group showed almost no change in the tooth mass removed after one week of training on the phantom head, while VR participants tended to remove less tooth structure. Hence, it could be concluded that the VR simulator may contribute to training for minimal cutting of the tooth. The reasons for this could be that the VR simulator enables unlimited trials during training with visually and haptically realistic teeth and tool models, and that the VR simulator provides detailed feedback on tooth volume loss as well as hand movement pattern at the end of each trial.

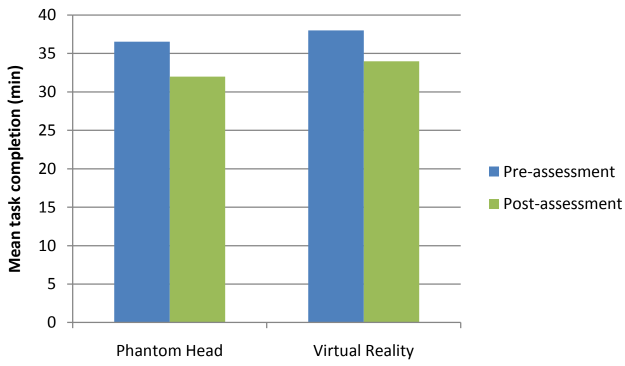
In summary, the data suggests that the VR dental simulation, when applied correctly to skill training, succeeds in reducing errors and thus improving performance in physical setting. Utilizing the simulator with haptic feedback and micro-CT tooth models maybe justified for skill development in dental procedures such as access opening and crown preparation. While the simulator could have potential to achieve the same results for other procedures, complicated operations such as root canal therapy and periapical surgery require the use of a flexible endodontic file (Figure 3.1c) or rotary file, demanding further enhancement of the simulator. Finally, our evaluation was done on extracted teeth instead of human patients in the operating room to prevent complications involved in actual patient care such as patient cancellation and case standardization. Future experiments could be performed with real patients to demonstrate the robustness of the simulator in operative performance.



(a)



(b)



(c)

Figure 3.7: Pre- and post-assessment comparing between control group (phantom head) and experiment group (virtual reality). (a) Mean error scores. (b) Tooth mass removed. (c) Task completion time.

Chapter 4

Automatic Dental Skill Assessment with Virtual Reality Simulator

Assessment of the quality of a performed procedure is important for students to track their progress to achieve better results (Hauser & Bowen, 2009). Traditional methods for evaluating surgical performance and skill acquisition during training is usually conducted by having an expert surgeon observe a *procedure* or only a final *outcome* and provide feedback. However, there are many concerns with this approach. The first is the limited availability of expert supervision in a training session with many students. This makes it difficult for instructors to observe a complete procedure by every student and thus often results in evaluation of dental outcome only. Nevertheless, only evaluating outcome for every student consumes much of an instructor's time, especially when the student-to-instructor ratio is high. The second is that the level of detail in a human assessment is limited. Grading performance could vary from one evaluator to another, subject to various factors. Finally, outcome assessment is usually limited to measurement of task completion time and number of errors. These measures do not characterize operator movements (e.g., position, orientation, or speed) during the steps required to achieve the desired outcome. The operator who has more accurate movements may take more time to complete a procedure. This speed-accuracy trade-off is a well-known phenomenon in motor control (Rose, 1997).

VR simulation has the potential to address these issues with its advantage of recording data about the environment and the user's precise actions for further analysis. This provides an opportunity to develop an objective method to fairly evaluate a student's performance. Unfortunately, only a few papers on dental simulators discuss this possibility. A recent commercial dental simulator for tooth preparation (VOXEL-MAN, 2011) claims to provide performance assessment functionality, but information about its algorithms and techniques is limited.

While repetitive practice is a benefit existing in most dental simulators, allowing students to practice without receiving feedback on their performance can eventually lead to poor results. One possible solution is to have an expert surgeon observe a student's procedure or outcome within the VR environment. However, the demand for expert supervision will decrease the usefulness of the system for self learning. Therefore, it is clear that a practical VR dental simulator should be supplied with algorithms to assess surgical expertise, and that additional objective measures are needed to quantify surgical performance improvements.

This chapter is based on Rhienmora, Haddawy, Khanal, Suebnukarn & Dailey (2010). We first discuss existing techniques in surgical performance assessment. Then, we describe our objective dental performance assessment based on user actions recorded by our VR crown preparation simulator. We provide experimental results and a discussion at the end.

4.1 Related Work in Performance Assessment with Simulators

There has been related work in surgical performance assessment with VR simulators or surgical robots. Some of this work involves assessment of surgical outcome. In a mastoidectomy simulator, Sewell et al. (2007) estimated the probability that each bone voxel is removed by a novice and by an expert, and implemented a naïve Bayes classifier to determine if the outcome was performed by an operator at a particular skill level. Later, they proposed a technique to assess bone removal skill by counting the number of bone voxels with high expert removal probability that were not removed by the user, and the number of bone voxels with low expert removal probability that were removed by the user. Their results show that this simple metric correlates well with instructors' ratings (Sewell et al., 2008). Another outcome assessment technique was proposed by Forsslund et al. (2009) in their wisdom tooth extracting simulator. They compare the amount of bone removed in each tooth structure by a student with that by an expert. This technique, however, disregards the fact that the same amount of bone removal does not imply the same cut shape.

Taking advantage of the recording features of surgical simulators, some work has utilized process-related data or user actions to assess a user's ability to perform a procedure correctly. Rosen et al. (Rosen et al., 2002; Rosen, Solazzo, Hannaford, & Sinanan, 2001) present a technique for objective evaluation of laparoscopic surgical skills using hidden Markov models (HMMs). They develop expert and a novice models based on force/torque information recorded from laparoscopic performances from each respective group. The accuracy of their expert/novice classification is 87.5 percent. Mackel et al. (Mackel, Rosen, & Pugh, 2006) collected data from five active contact force sensors distributed in the E-Pelvis physical simulator and developed a methodology to evaluate clinical competence of physicians using Markov chain models. Their evaluation shows that 92 percent out of the 82 test subjects were classified into their correct skill levels. Sewell et al. (2007) also present various procedure-related metrics for automated evaluation of surgical competency in the context of mastoidectomy simulation. Some of the metrics that are strongly correlated with experts' assigned scores include the amount of bone removed during proper and obscured visibility and the amount of bone in dangerous regions removed while excessively large forces are applied. They also experimented on using HMMs to assess the bone removal process with selected features including force magnitude, drill position, distance to facial nerve, and suction position. Their models can correctly classify 85 percent of all test subjects (Sewell et al., 2008).

4.2 Evaluating User Dental Performance with HMMs

To achieve objective dental performance assessment based on user actions, we first conducted interviews with experienced dentists. This led to a hypothesis that among the important features for distinguishing experts from novices in dental surgery are tool movement (position and orientation of the tool over time) and the level of force applied during a procedure. We visualize these features by plotting tool movement from a simulated crown preparation of an expert and a novice in three dimensions in Figure 4.1 and the average magnitude of the force applied by an expert and a novice over each stage of the procedure in Figure 4.2. We also show the average time taken at each stage of crown preparation by expert and novice in Figure 4.3.

The difference between expert and novice performance in tool movement can be clearly seen in

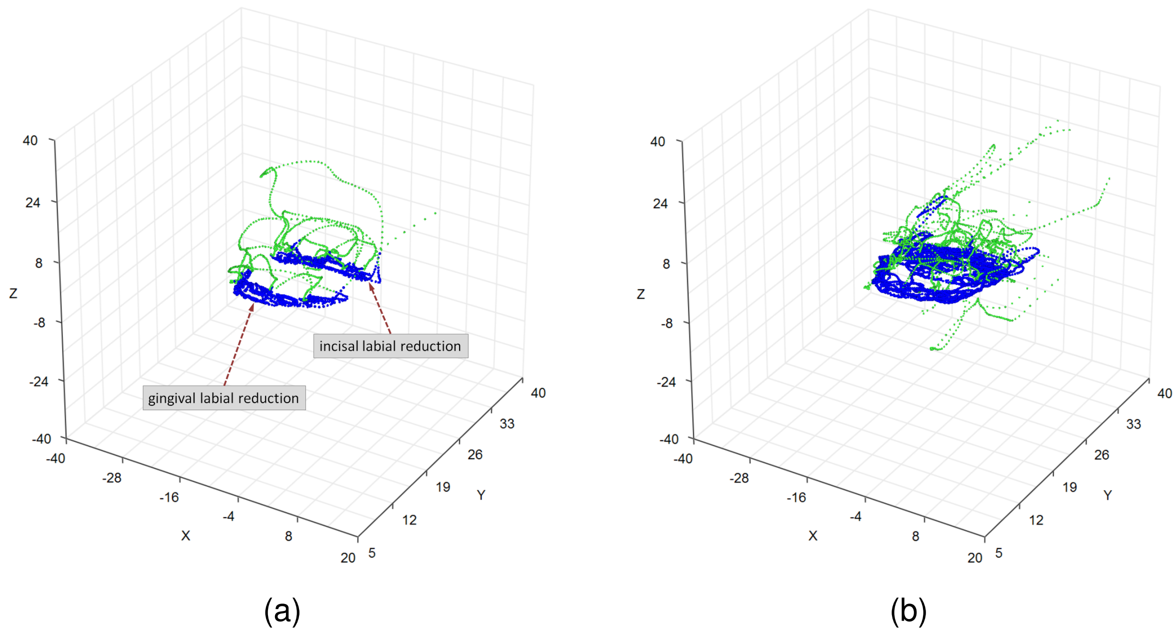


Figure 4.1: Example tool paths of an expert (a) and a novice (b). Expert movement is more consistent throughout the operation.

Figure 4.1 and Figure 4.2. In Figure 4.1, the lighter dots represent the position of the tool when cutting was not activated via the foot pedal whereas the darker dots represent the position of the tool while cutting. We see from the figure that the expert's movement is more deliberate and economical throughout the operation. Moreover, we can also see proper separation of gingival labial reduction and incisal labial reduction (refer to Stage 11 and 12 in Figure 4.4) but we cannot see proper separation of the two reductions in the novice plot. In Figure 4.2 we see that the force used at each stage of the procedure by experts and novices is also different. The force applied by the expert varies at each stage of crown preparation and is generally greater than the force applied by the novice, which is more uniform. These suggest that tool movement patterns and force feedback from the haptic device might be valuable in distinguishing experts from novices.

4.2.1 Materials and Methods

The simulator used in this experiment is the surface-based dental simulator described in Section 2.2. The task was to perform a 13-stage partial crown preparation on the upper left central incisor. This is a standard procedure taught to novice students at Thammasat University (Figure 4.4). The partial process was chosen instead of a full process to avoid conflating tool skills with indirect vision skills requiring a dental mouth mirror.

We propose the hidden Markov model (HMM) as a statistical tool to objectively assess dental surgical performance based on the measured data about the operator's actions. HMMs have been used extensively and shown to be effective in applications such as gesture recognition (Lee & Kim, 1999) and speech recognition (Rabiner, 1989). They also have been used for modeling human operator skills

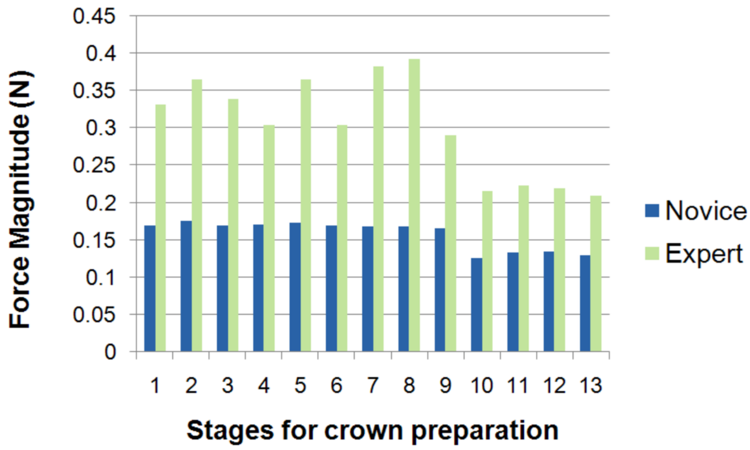


Figure 4.2: Example of average force applied by an expert and a novice during 13 stages of simulated crown preparation. Experts tend to use more force with more variation across the stages.

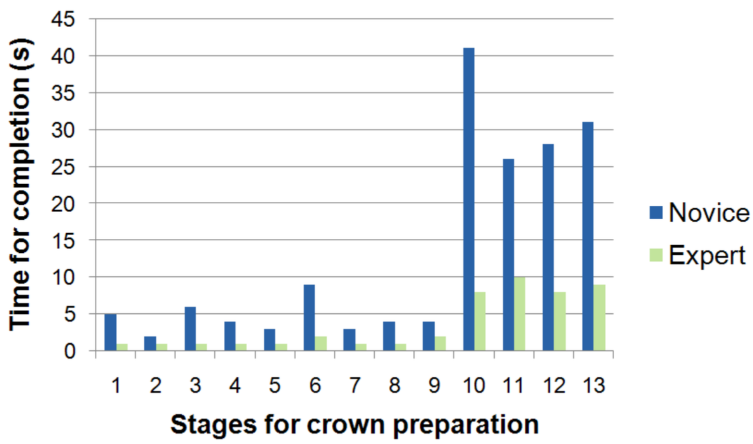


Figure 4.3: Average time taken at each stage of tooth preparation by expert and novice. The expert performs the procedure substantially faster than the novice does.

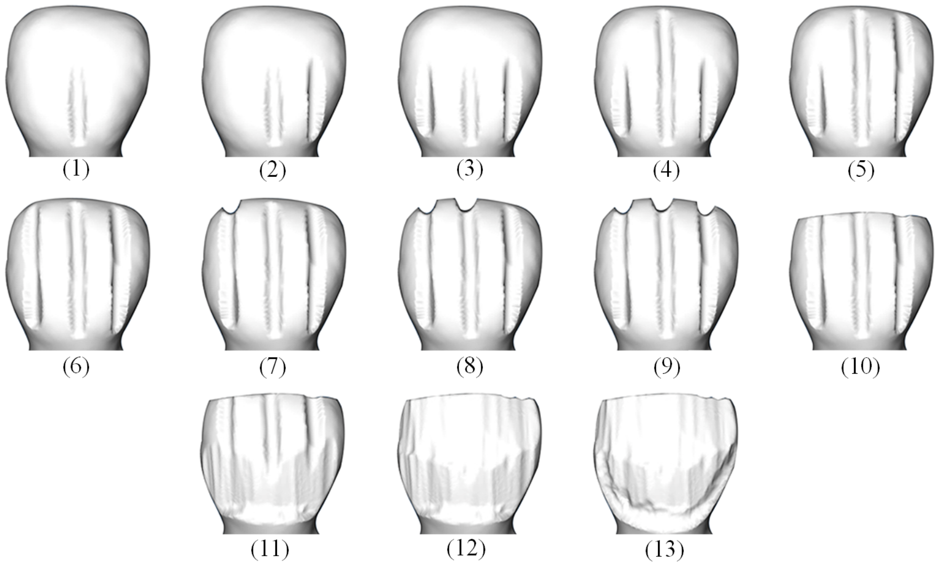


Figure 4.4: Thirteen stages of crown preparation on the labial and incisal surfaces of a tooth. Stage 1: labial gingival guiding (central). Stage 2: labial gingival guiding (mesial). Stage 3: labial gingival guiding (distal). Stage 4: labial incisal guiding (central). Stage 5: labial incisal guiding (mesial). Stage 6: labial incisal guiding (distal). Stage 7: incisal guiding (distal). Stage 8: incisal guiding (central). Stage 9: incisal guiding (mesial). Stage 10: incisal reduction. Stage 11: labial reduction (gingival). Stage 12: labial reduction (incisal). Stage 13: labial cervical margin.

and transferring them to robots (Hovland, Sikka, & McCarragher, 1996). Recently, HMMs have been applied to model complex tasks such as surgery, specifically in automatic assessment of surgical performance in laparoscopy (Rosen et al., 2002, 2001), pelvic examination (Mackel et al., 2006; Mackel, Rosen, & Pugh, 2007), and mastoidectomy (Sewell, Morris, Blevins, Agrawal, et al., 2007; Sewell et al., 2008). These applications suggest that HMMs have high potential to provide accurate models for assessing dental surgical expertise.

We conducted an experiment to test the ability of a HMM to recognize and classify an observed procedure as novice or expert, based on a set of recorded important features including the applied force during the simulation and the positions and orientations of the dental tool.

We recruited five novices (fourth-year dental students, ages 20-22 years) and five experts (ages 35-45 years) from the Faculty of Dentistry of Thammasat University to participate in the study. All participants were known to the researchers. All of the novices had experience using dental handpieces in cavity preparation from an operative preclinical course but no prior experience performing crown preparation. All of the experts had professional training and experience in prosthodontics. All participants were right-handed. None of the participants had previously received any skill training using a haptic virtual reality system. All participants rated themselves as good or excellent computer users.

All participants were instructed to follow the 13-stage preparation process (Figure 4.4) with the surface-based dental simulator. We verified that each participant performed all 13 stages in the correct order. Each participant performed five trials of the task. The last trial was used for data analysis.

Our simulator monitors and records all of the data relevant to a user's activity while he/she performs the simulated crown preparation. The data include all of the important features mentioned previously as well as the active status of the drill and the indices of the vertices being cut on the tooth surface. We manually labeled the preparation stage transitions in order to facilitate later evaluation of automatic stage segmentation strategies.

After collecting the data from all participants, we built separate discrete linear HMMs to model novice and expert procedure sequences. In our model, the hidden states are the thirteen stages of partial crown preparation. The observed feature set includes the applied force recorded during the simulation as well as the positions and orientations of the dental tool. The manual labeling of preparation stage was *not* used in training or testing. The models were free to assign sequence elements to any of the hidden states as required to model the data. We normalized each feature element to the same range by z-scaling. Since we use discrete HMMs, we first converted the feature vectors into symbols using the k-means clustering algorithm. As each of the thirteen stages in crown preparation has a distinct force and movement pattern, we chose k=13.

According to Rabiner (1989), four elements should be defined in order to specify HMM λ: (1) the number of states in the model; (2) the state transition probability distribution matrix A; (3) the observation symbol probability distribution matrix B; and (4) the initial state distribution vector π. The HMM can thus be defined by:

$$\lambda = (\mathrm{A}, \mathrm{B}, \pi)$$

In our system, the number of states is 13. We trained the novice and expert HMMs by adjusting the model parameters $(\mathrm{A}, \mathrm{B}, \pi)$ to maximize the probability (P) of the training sequences (O) as follows:

$$\begin{aligned} Given &: \lambda = (\mathrm{A}, \mathrm{B}, \pi) \\ Adjust &: \mathrm{A}, \mathrm{B}, \pi \\ To\, maximize &: P(O|\lambda) \end{aligned}$$

After training, we calculated the probability and log likelihood of the test sequences under the novice and expert HMMs using the forward algorithm (Rabiner, 1989) to find the model that best describes the test sequence data. When the log likelihood of a test sequence under the novice HMM is greater than that under the expert HMM, the system classifies the test sequence as a novice sequence; otherwise, the system classifies it as an expert sequence.

We performed five-fold cross validation. We used a different k-means for every cross validation fold and the same k-means for the novice and expert model in the same fold. For each fold, we trained the novice HMM with four novice and four expert sequences. To determine the accuracy of the method, after training the two HMMs in each fold, we fed the test novice and expert data to each model.

4.2.2 Results

The average log likelihood of all sequences across all five folds for the two HMMs is shown in Table 4.1. In every cross validation fold, the log likelihood of every test sequence under its corresponding HMM was higher than that under the other HMM. These results demonstrate the ability of the HMM to distinguish between novice and expert performance with 100% accuracy. However, we

Table 4.1: Average log likelihood results for expert and novice performance sequences.

	Log likelihood for Expert HMM	Log likelihood for Novice HMM
Expert Performance	-3.574×10^{3}	-2.229×10^{6}
Novice Performance	-6.272×10^{5}	-3.494×10^{3}

do note that the number of participants (10) was relatively small.

4.3 Discussion

In this study, all process-related data (e.g., force used, position and orientation of the dental tool) is readily available for recording by the simulation software. This data is not available, or difficult to achieve, in conventional skill training environments. Based on the recorded data, our system objectively assesses the performance and provides tutoring feedback without the presence of a human expert.

The accuracy of our automatic performance assessment system using HMMs is high. The system can correctly classify the categories of all the test sequences. However, the number of participants in our study was relatively small and most had similar levels of expertise within their categories which might introduce bias. In this study, we assumed and verified that each participant followed all stages in the correct order; therefore, errors involving deletion or insertion of stages are not considered. Experiments with more participants and various skills levels will be conducted in future work.

More complex procedures might involve complicated pathways such as circular motion. Moreover, advanced students might perform a procedure in a different direction or omit some procedure stages. We will certainly need more sophisticated reasoning as we move to more challenging tutoring scenarios with more advanced students.

Chapter 5

Post-Simulation Automatic Tutoring Feedback and Training Enhancement Strategies

While assessment of surgical skill is important for students to track their progress, it tells them very little about how to improve their skills and competencies. To achieve such improvement, students usually rely on instructors to supervise and provide tutoring feedback (Hauser & Bowen, 2009).

Simulators should be able to provide tutoring feedback to users in order to reduce the time and effort required for instructors to supervise and tutor students. Thus, incorporation of strategies for training and generating objective tutoring feedback with quality comparable to that of human tutors is an essential part of simulator development. This could add more educational value to a training system and enable it to serve as an intelligent, autonomous virtual instructor for surgical skill acquisition.

In the previous chapter, we demonstrated that instrument movement and the level of force applied during a procedure are among the important features for distinguishing experts from novices in dental surgery. In this chapter, we further use these features to derive useful tutoring feedback for students to improve their skill. We first describe mechanisms for objective tutoring feedback generation. Then we explain the use of augmented kinematic feedback and show how it could contribute to dental skill acquisition. Finally we cover various training techniques to help in transferring of skills needed to perform dental procedures by utilizing visual and haptic record/replay.

5.1 Objective Tutoring Feedback

An intelligent virtual tutor should act as a real instructor in providing trainees using the simulator with feedback on the important aspects of proper dental surgical techniques. In a traditional training method such as phantom head, an instructor usually provides feedback by reviewing the final tooth outcome without observing the whole operation process. The main reason for this is that is the normally high student-to-instructor ratio. The limitations of outcome review are that an instructor is not able to evaluate how a student gets to the end result and that the subsequent evaluation and guiding become subjective. Even in a situation where an instructor could look closely at a student's operation, it is still difficult to teach some surgical aspects such as proper amount of applied force.

We propose the use of dental surgical features in providing objective tutoring feedback to trainees using the simulator. In a simulated crown preparation, the average position, orientation, force, and main axis of force direction differ between the procedure stages. In stage (1) (Figure 5.1), for example, force and tool movement is mostly in the minus Y direction, while in stage (5) (Figure 5.1), force and tool movement progress mostly in the minus Z direction. We can use these unique forces, positions, orientations in each crown preparation stage as the basis of our feedback generation mechanism. These characteristics can be observed by the simulator and compared to a gold standard in order to generate useful feedback. Examples of our feedback strategy considering applied force for stage (1) and (5) are shown in Table 5.1.

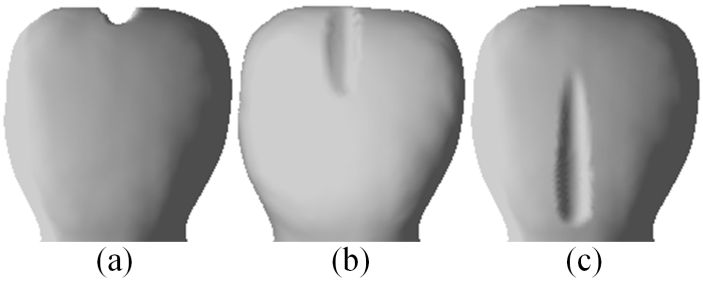


Figure 5.1: Examples of crown preparation stages. (a) Stage 1: mid-incisal depth cut. (b) Stage 5: mid-upper-labial depth cut. (c) Stage 9: mid-lower-labial depth cut.

Table 5.1: Examples of feedback generated in stages (1) and (5) considering only applied force. Subscript *e* indicates the expert average value (out of five experts) with one standard deviation while *n* indicates the current novice value.

Stage	F_x (N)	F_y (N)	F_z (N)	Feedback
1_e	0.103±0.037	0.480±0.047	0.106±0.023	*"Force in minus Y direction*
1_n	0.026	0.164	0.091	*should be 3 times higher"*
5_e	0.040±0.014	0.038±0.019	0.237±0.053	*"Force in minus Z direction*
5_n	0.028	0.019	0.129	*should be 2 times higher"*

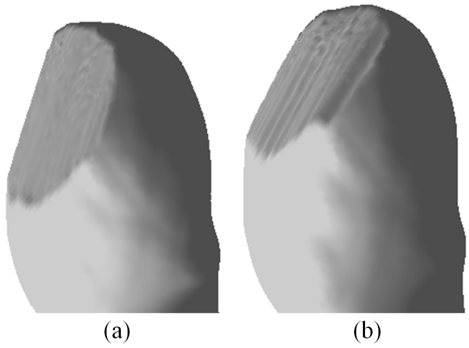


Figure 5.2: Example of a difference in tool orientation between an expert (a) and a novice (b).

We generate feedback for position and orientation using the same strategy. For example, Figure 5.2 shows a stage in which a novice's tool orientation was very different from that of experts. In this case the feedback generated was "try to lower the degree of rotation around the X axis." For states in which the operator does well, we generate a compliment such as "well done."

5.1.1 Experimental Evaluation

The main objective of this experiment was to test the overall acceptability of the training feedback generated by the simulator.

The simulator loaded the log files of all five novices collected during the previous experiment described in Section 4.2.1 and replayed the procedure, one novice at a time. During playback, the system used the manually specified stage labels to segment each sequence into the 13 stages of the preparation procedure. The system observed the characteristics of each stage, computed statistical results, compared them with the statistics acquired from experts, and then generated and displayed the tutoring feedback messages on the screen. An expert examined both a replay of the novice procedures and the feedback generated by the system. The corresponding force values along three axes were also plotted on the screen during replay to aid understanding of how the forces were applied by the operator.

During the experiment, a total of 65 tutoring feedback messages were generated. The expert was asked to rate the acceptability of each feedback message on a scale of 1-5, where 1 implied unacceptable, 2 implied not quite acceptable, 3 implied not sure, 4 implied close to acceptable, and 5 implied acceptable.

5.1.2 Results

The reader may refer to Figure 5.1 for the desired outcomes of stages (1), (5) and (9).

Table 5.2 shows the expert evaluation of some of the system's feedback messages. During stage (5),

Table 5.2: Part of the expert evaluation form for stages 1), 5) and 9). Subscript *e* indicates the expert average value (out of five experts) with one standard deviation while *n* indicates the current novice value.

Stage	F_x (N)	F_y (N)	F_z (N)	Feedback	Acceptability
1_e	0.103±0.037	0.480±0.047	0.106±0.023	*"Force in minus Y direction*	4
1_n	0.026	0.164	0.091	*should be 3 times higher"*	
5_e	0.040±0.014	0.038±0.019	0.237±0.053	*"Force in minus Z direction*	5
5_n	0.028	0.019	0.129	*should be 2 times higher"*	
9_e	0.064±0.024	0.035±0.019	0.285±0.033	*"Force in minus Z direction*	3
9_n	0.108	0.115	0.159	*should be 2 times higher"*	

during which the main force should be applied in the minus Z direction, the average force applied by a user in this direction was not within one standard deviation of the expert mean (the acceptable range was 0.184 N - 0.290 N). Since the novice's average force was around half that of the expert, the generated feedback, "Force in minus Z direction should be 2 times higher," was rated as acceptable (score 5).

For stage (9), however, even though the situation in the minus Z direction was almost the same as in stage (5), the feedback ("Force in minus Z direction should be 2 times higher") was rated as not sure (score 3). The expert noticed that, during this stage, the force value in X and Y were quite high although they should have been close to zero. There might be two causes for this behavior; either the novice did not know the main direction of the force in this stage (minus Z) or he/she knew but could not control the tool to move in the right direction. The expert suggested giving a tutoring hint such as "Do you know that minus Z should be the main direction of force in this stage?" This kind of hint would be especially useful in online training as the system can observe a novice's reaction after the feedback is given. Note that even though we have not yet applied this strategy, the system was capable of detecting the behavior as the forces in the X and Y directions (0.108 N and 0.115 N, respectively) were both more than one standard deviation from the expert means.

For stage (1), the generated feedback, "Force in minus Y direction should be 3 times higher," was ranked as close to acceptable (score 4). The expert commented that a novice could accidentally damage a tooth in this stage if he/she tried to applied too much force; therefore, she suggested that the feedback could possibly be only "2 times higher" rather than "3 times higher."

These expert suggestions could be integrated to the feedback generation mechanism to improve recommendations. However, feedback such as "...force should be 2 times higher...," could still be confusing as students, especially novices, are sometimes unable to judge their own effort during the operation. These issues and proposed solutions will be discussed in Section 5.3.

The distribution of acceptability ratings for all 65 training feedback messages generated by the system are shown in Table 5.3. The average score assigned by the expert for the generated feedback was 4.154 out of 5.

Table 5.3: Distribution of feedback acceptability ratings for 65 generated feedback messages. The average score was 4.154.

	Feedback Acceptability Ratings				
	5	4	3	2	1
Frequency	23	32	7	3	0

5.2 Augmented Kinematic Feedback

In our simulator, we provide *knowledge of performance* (KP) feedback information in addition to the *knowledge of result* (KR) feedback they normally receive from outcome review. While knowledge of result is error information obtained from a comparison of the desired and actual outcomes (e.g., "the pulpal depth was 1 mm too deep"), knowledge of performance represents information about the comparison between the desired and actual parameters of the treatment process (e.g., whether the handpiece was held perpendicular to the long axis of the tooth when it should have been).

A large body of research in motor learning has identified information feedback, especially KR, as one of the most critical variables that influence performance, retention, and skill transfer in motor learning (Schmidt, 1982) as well as dentistry (Feil, Reed, & Hart, 1986). Alternative approaches have focused on the influence of augmented kinematic feedback or KP, defined as post-response kinematic information about some aspect of the movement pattern (Young & Schmidt, 1992). Several types of movement pattern feedback have been shown to be effective in enhancing the performance of various skills in general (Newell, Carlton, & Antoniou, 1990). However, limited research has been conducted on the impact of augmented kinematic feedback on the learning process of dental skill acquisition.

Here we utilize the paradigm developed for augmented kinematic feedback in our VR dental simulator. The simulator is able to extract real-time kinematics from an operator's performance. We provide the design of a randomized controlled trial to investigate the role of several variations of movement-pattern feedback on dental skill acquisition and retention performance compared to those without augmented feedback.

5.2.1 Experiment on Augmented Kinematic Feedback

The system recorded data associated with the performance process including force utilization along the x, y, and z axes (x:bucco-lingual direction, y:mesio-distal direction, and z:long axis of the tooth) and mirror views used in relation to the tooth. To quantify the extent of bimanual dexterity, a coordination analysis was conducted to evaluate the direct relationship between the mirror positions and the handpiece. Sightline angles were classified into four views. View 1 denotes an acute angle with the left upper part of the sighted surface. View 2 denotes an acute angle with the left lower part of the sighted surface. View 3 denotes an acute angle with the right lower part of the sighted surface. View

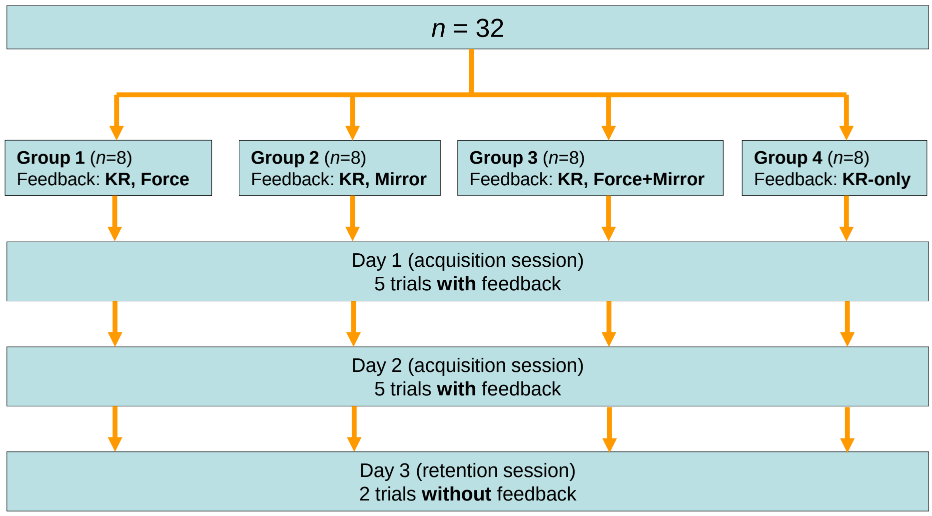


Figure 5.3: Flowchart of participants through trials.

4 denotes an acute angle with the right upper part of the sighted surface.

The augmented kinematic information about force utilization and mirror position during tooth preparation was given after the students performed endodontic access opening on the upper first molar using the simulator. The augmented kinematic feedback variables examined involved force utilization (F) and mirror views (M). This created three experimental conditions that received outcome review (KR) along with augmented kinematic feedback (F, M, F+M), and one control condition that received only outcome review (KR-only).

Method

We recruited 32 sixth-year dental students at the Faculty of Dentistry, Thammasat University, Thailand. All participants were right-handed and had no prior experience with the simulator. The participants were randomly allocated to the three experimental conditions and one control condition such that each group had eight participants.

The participants' task was to perform access opening on the upper right first molar using indirect vision with a virtual dental mirror in our VR simulator. The participants were informed to follow four procedure steps:

1 : Cut into palatal pulp horn

2 : Extend the opening laterally to the mesio-buccal canal orifices

3 : Extend the opening laterally to the disto-buccal canal orifice

4 : Extend the opening laterally to the palatal canal orifice

After familiarization with the system interface (but not with the task), the participant performed in acquisition sessions on each of two consecutive days (a total of ten trials), with a retention session

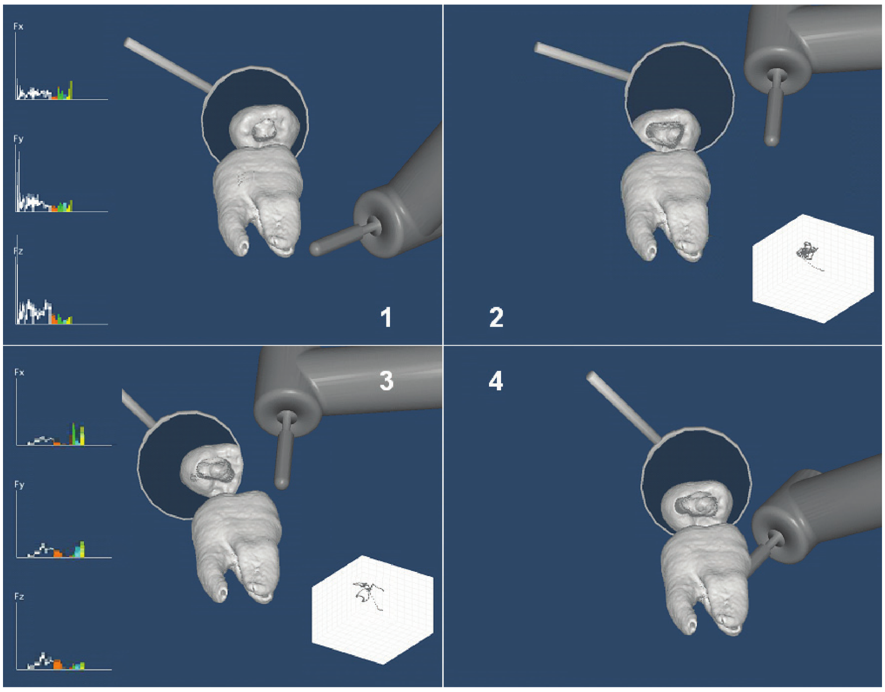


Figure 5.4: Screenshots of the video playback of student performance and augmented kinematic feedback of each group. Groups were as follows: group 1, force (upper left); group 2, mirror (upper right); group 3, force and mirror (lower left); and group 4, KR-only (lower right). Force utilization in each procedure step was presented as three graphs (F_x, F_y, F_z). The mirror view used was tracked from the relationship between the mirror positions and the handpiece.

on the third day a week later (Figure 5.3). On the first two days, each participant was provided with the overall performance score (KR) after each trial. The performance score takes into account six evaluation parameters (visibility of the canal orifices, four axial walls, and pulpal floor). The score for each evaluation parameter falls in the range of 0 (lowest) to 3 (highest). Thus, each trial was assigned an overall preparation score between 0 and 18; higher is better. In addition to KR, the participants in the experimental groups were presented with the video playback of their performances and experts performance along with their respective augmented kinematic feedback after each trial (Figure 5.4). An example video playback screen of student's and experts performance along with force information as augmented feedback is shown in Figure 5.5.

On the third day, a week later, a retention test consisting of two trials without any kinematic feedback was carried out. These trials served as our basis for measuring permanent capabilities acquired with practice in participants.

Results

The mean scores for each group in acquisition (Day 1 and Day 2) and retention (Day 3) sessions are shown in Figure 5.6.

Average scores for Day 1 (trial 1 through 5) were approximately seven points on the first trial and then generally increased throughout the first acquisition session. For the majority of the trials in this

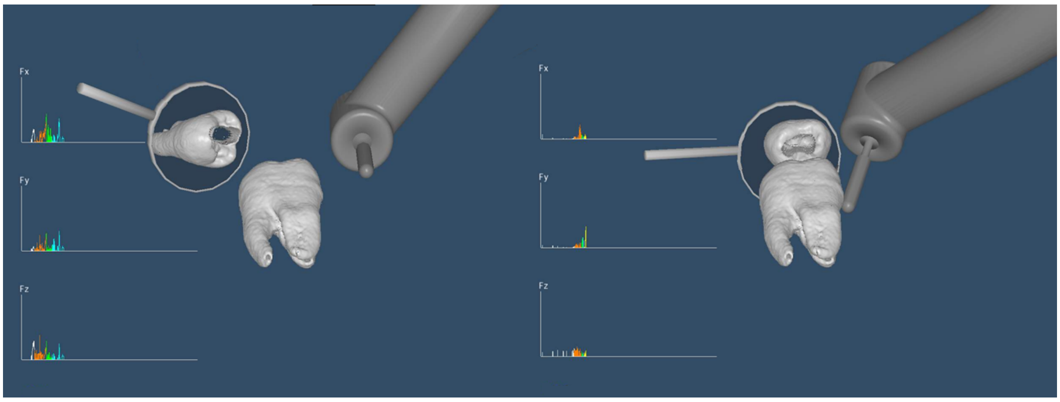


Figure 5.5: Video playback of student's and expert's movement along with force information as augmented feedback

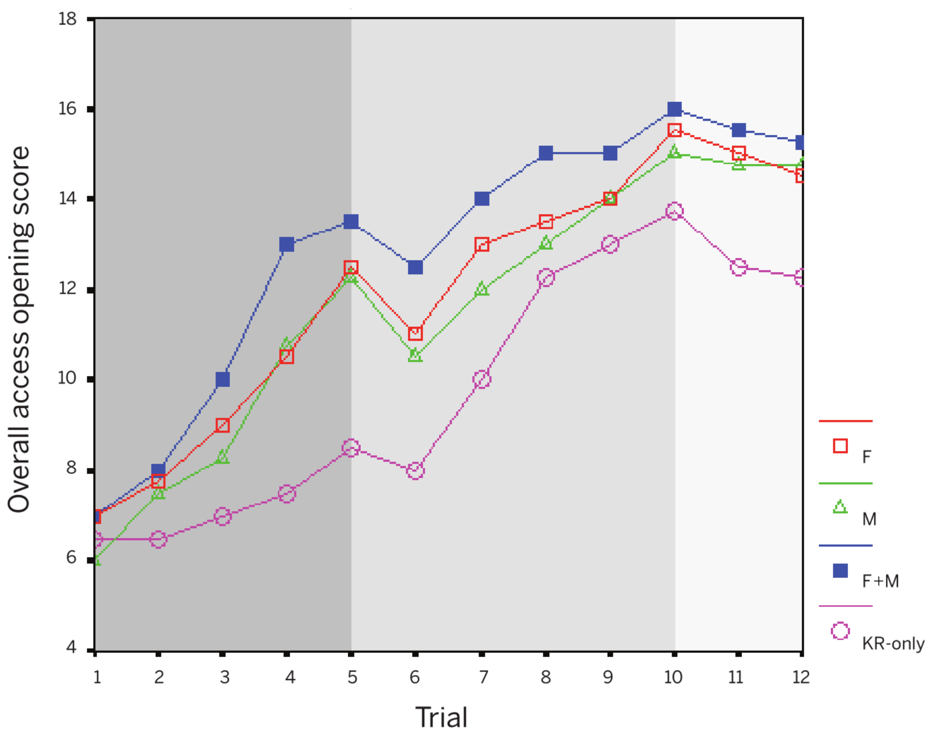


Figure 5.6: Mean overall access opening score for the four feedback conditions during acquisition (trial 1 through 10) and on the retention test (trial 11 and 12).

phase, the groups that received augmented kinematic feedback (F, M, F+M) had higher mean scores than the group that received only outcome review (KR-only). Overall, scores for the F+M group were the highest, whereas the KR-only group had the lowest mean score on Day 1. The scores on Day 2 of the acquisition session (trial 6 through 10) generally increased throughout the session. For the majority of the trials in this phase, the augmented kinematic groups had higher mean scores than the KR-only group. In the retention session on Day 3 (trial 11 and 12), the F+M group performed most competently followed by F and M groups. The KR-only had the lowest scores on Day 3.

A comparison between experimental and KR-only group indicated that, in the early phase of skill acquisition, all groups that received kinematic feedback along with outcome review performed more proficiently than the group that received only outcome review. In the retention test in which kinematic feedback was omitted, all three kinematic feedback groups still performed better than the KR-only group. This preliminary study demonstrates that the augmented kinematic feedback condition led to more effective performance over conventional outcome feedback.

5.3 Visual and Haptic Replay of Dental Procedures

In the early phase of skill acquisition (cognitive stage), students are required to understand the procedures associated with a complex motor task (Fitts & Posner, 1967). At this stage, students try to develop a plan of movement by assimilating the correct visual and verbal information. For later stage (associative stage), students practice frequently to find the most effective way to accomplish the task (Fitts & Posner, 1967).

In a conventional training, students progress through these stages of skill acquisition by observing an instructor's performance and then trying to imitate it by themselves. As instructor's time is a scarce resource, it is common that students has to learn from instructional videos and try to replicate what they have seen.

Unfortunately, these skills are difficult to learn, especially by merely observing. It is desirable to have a better training aid that helps transfer the expert experience such as ergonomic hand movements and proper use of force, directly to students.

In this section, we propose five intelligent training strategies for dental skill acquisition using our VR simulator. These proposed training modes could shorten the long and gradual skill acquisition process by providing more engaging, interactive learning environments. These modes range from interactive visual replay of expert performance to experiencing expert movement and force, as follows:

Mode 1: Interactive visual replay from several viewpoints

A dental phantom-head training system optionally comes with a video camera mounted with a light source to record a video of an ongoing dental operation (Figure 5.7). Students can use this camera to record and later review videos of their operations. However, with only one camera, students could view the recorded video only from one view point at a time (Figure 5.8). If they have a chance to replay and examine a procedure from different angles, some important aspects of a performance such as common mistakes could be easily identified and then corrected.

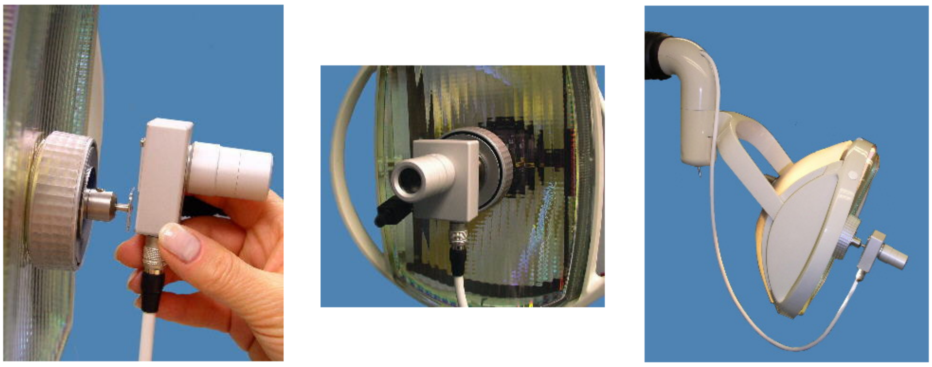


Figure 5.7: A video camera mounted to a light source to record dental performance (ThirdEye Video by Verlag Neue Medien).

Figure 5.8: A snapshot of a dental video recorded with a video camera attached to a light source

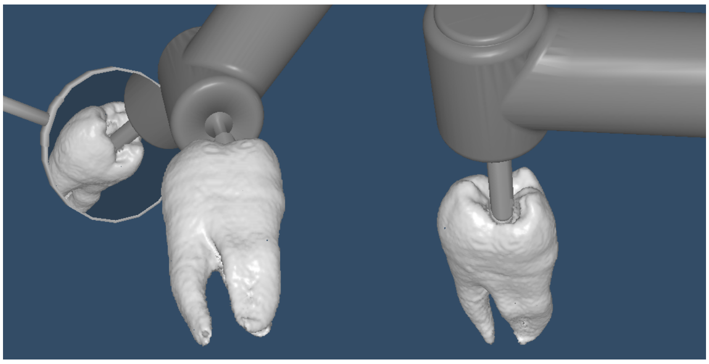


Figure 5.9: A visual replay of a simulated dental procedure can be view in any angle and scale for training Mode 1.

One advantage of a simulation system is a record/replay feature. Data about a dental procedure performed in a VR simulator can be recorded and then replayed in whole or emphasizing a particular section. Our VR simulator allows for students to record their performances and for instructors to record training scenarios. More importantly, students can view a replay from any direction and scale by rotating, translating, and zooming. This makes it easier for them to learn correct techniques from a replay of an instructor, or examine their own procedures to spot mistakes. To enable this feature, a simulator must record raw tool state data including position, orientation, and drill status for the whole operation and then save it to a raw data file. This is in contrast to recording only what is displayed on a simulator screen to a video file, which will share the same disadvantage as training with videos.

The replay function works by reading in the tool positions, orientations, and drill states from a raw data file rather than getting these values from a haptic device. The simulator then applies these values to control the virtual instrument and move it as previously recorded. All computations such as collision detection and tooth material removal is computed normally to reproduce actual conditions encountered by an instructor. The result is visualized on screen and a user is allowed to change viewing direction or zoom level with a mouse (Figure 5.9).

A student can also specify a degree of transparency for each part of a tooth image. This feature could assist a student by revealing internal critical structures while performing a procedure. For example, Figure 5.10 shows transparent enamel and dentin for a student to clearly see a pulp chamber roof which is a critical structure in an access opening procedure. Normally, a student cannot see the pulp while drilling and must rely only on haptic feedback to identify this area.

Mode 2: Passive trajectory learning with hand guidance

The inspiration for this training method came from calligraphy training, in which an expert holds and guides a student's hand while writing. This is regarded as a passive training method because students do not move their hands by themselves. This technique is quite efficient in early stages of skill acquisition in calligraphy as well as many sports (Figure 5.11).

This passive technique can be implemented in a dental simulator through position playback of experts' recorded performance and position control that applies to a haptic device stylus that is lightly held by a student. The training starts with the simulator replaying an instructor's performance by reading in the tool positions, orientations, and drill states from a raw data file and applies these values to

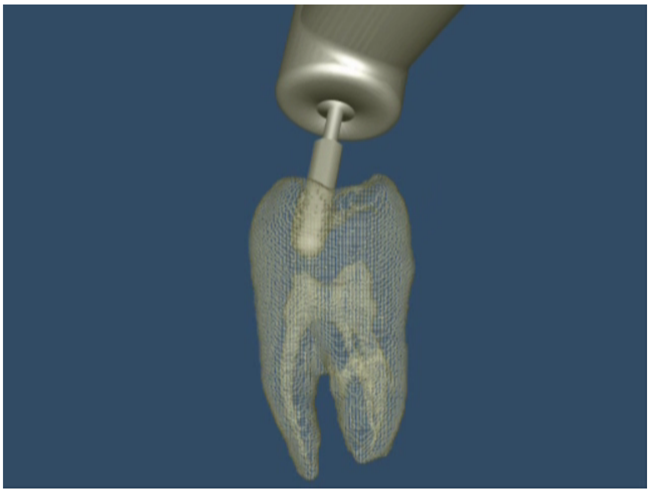


Figure 5.10: Enabling transparency to enamel and dentin reveals a pulp chamber.

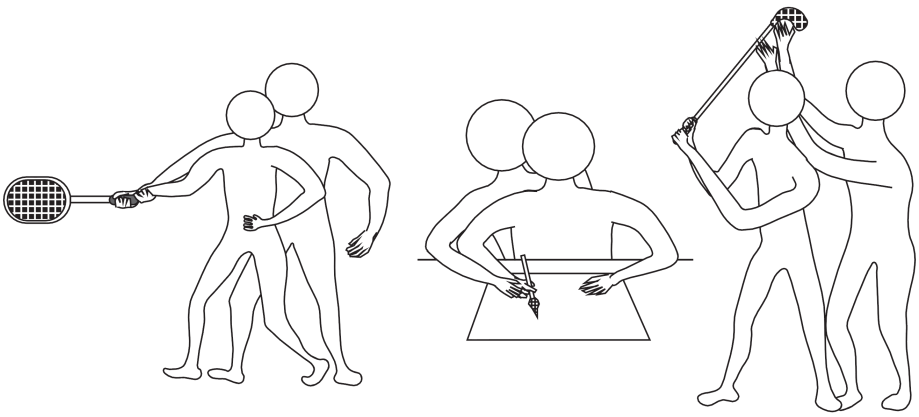


Figure 5.11: Hand-holding by an instructor is used in various training activities including tennis, letter writing, and golf. Picture taken from Yokokohji et al. (1996).

control the instructor's tool at a haptic rate of 1000 Hz. In each simulation loop of the replay, the simulator generates a force field centered at the tip of the moving instructor's tool. The force field has an influence over the haptic device stylus that it could eventually guide the stylus to move in the replaying trajectory. The amount of this guiding force is proportional to the magnitude of a distance vector $\Delta \boldsymbol{X}$ between the desired instructor's tool tip position $(\boldsymbol{X}_{instructor})$ and the student's tool tip position $(\boldsymbol{X}_{student})$

$$\Delta \boldsymbol{X} = \boldsymbol{X}_{instructor} - \boldsymbol{X}_{student}$$

and is computed as follows:

$$\|\boldsymbol{F}\| = \begin{cases} 0 & , \quad \|\Delta \boldsymbol{X}\| > \varepsilon_2 \\ \\ k\,\|\Delta \boldsymbol{X}\| & , \quad \varepsilon_1 \leq \|\Delta \boldsymbol{X}\| \leq \varepsilon_2 \\ \\ k\dfrac{\|\Delta \boldsymbol{X}\|^2}{\varepsilon_1} & , \quad \|\Delta \boldsymbol{X}\| < \varepsilon_1 \end{cases}$$

where k is a constant and ε_1 and ε_2 are threshold variables. The guiding force is zero when the positional difference between the two tools is greater than a threshold ε_2. In this case, it is assumed that the student either has not started moving the stylus near the instructor's initial position, or has abandoned the training by moving the stylus away from the guiding force field. If the difference between the two tool is between ε_2 and ε_1, the guiding force is linearly proportional to that difference. Finally, as the student's tool position gets closer than the small threshold value ε_1 to the instructor's tool position, the linear function is no longer appropriate as it could introduce instability in the resultant guiding force. In this case, the student could experience force *kicking* from a haptic device as $\boldsymbol{X}_{instructor} \approx \boldsymbol{X}_{student}$, especially when k is high. To solve this problem, Kolesnikov et al. (2009) suggest a quadratic function to ensure the stability of the computed force when $\|\Delta \boldsymbol{X}\| \approx 0$. We have experimented with this suggested function and found that it effectively reduces instability in this hand guiding mode. A related technique using a PD controller for passive guidance was implemented in a virtual palpatory training simulation (R. L. Williams, Srivastava, Conaster, & Howell, 2004).

While the haptic device stylus is being guided by the force field, an image of a dental tool that represents a haptic stylus is also rendered at the actual stylus position and moved according to the stylus. For the two tools that appear on the simulation screen, the one that has an effect on tooth cutting is the replayed instructor's tool. However, force computations for tooth collision and cutting are ignored as the haptic device motors are occupied with position control of the student's hand only.

Training in this mode, a student could learn the correct trajectory for a dental procedure by loosely holding a haptic device stylus while it is being dragged by the guiding force. This learning experience is quite similar to that in calligraphy training, as the student feels that his/her hand is being held and guided by an instructor (Figure 5.12). However, since we are using a haptic device that renders force but not torque, our simulator cannot haptically guide a student's hand into correct tool orientations. To alleviate this limitation, students could try to minimize orientation difference between the instructor's

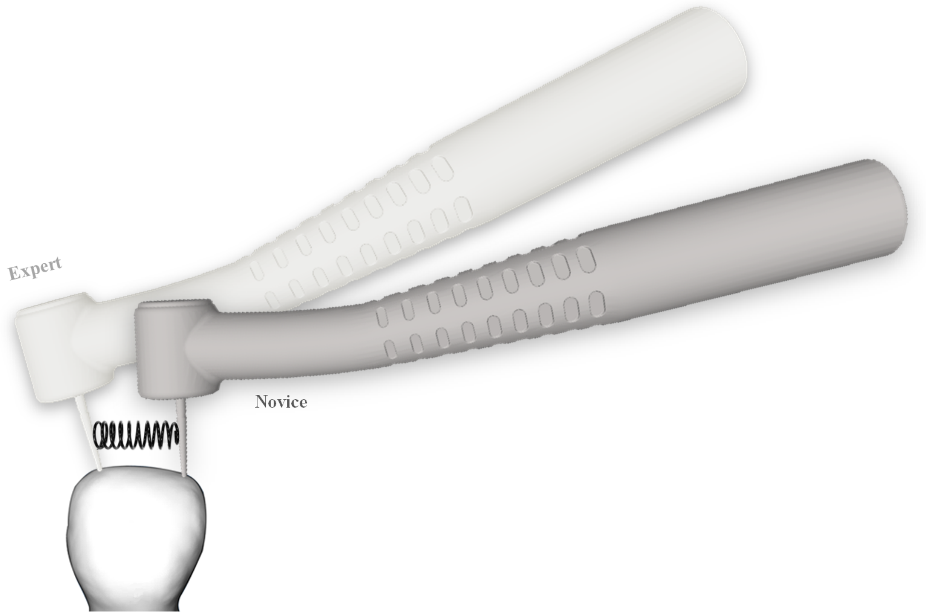


Figure 5.12: Passive trajectory learning with force guidance in training Mode 2. The expert's tool trajectory *drags* the novice's tool.

tool and the student's tool by manually orienting the stylus.

Mode 3: Active learning of tool trajectory, position, and orientation

After interactively examining an instructor's performance in Mode 1 and learning a correct tool trajectory with virtual hand guidance in Mode 2, students might be confident to control a virtual tool themselves while practicing. Our VR simulator offers three more training modes (modes 3, 4, and 5) that allow students to actively move a virtual dental tool in a training environment.

In Mode 3, there are two virtual dental tools in the environment: the tutor's tool and the student's tool. The tutor's tool is controlled by previously-recorded data. The student's tool is controlled interactively by a student with a haptic device (Figure 5.13). The task in this mode is to imitate the instructor's performance by moving the student tool to catch up and align as closely as possible with the tutor tool. After training in this mode, a student would be familiar with the correct trajectory for the dental procedure as well as proper tool positions and orientations along the trajectory.

The underlying mechanism of this training mode is quite similar to the visual replay mode (Mode 1) discussed earlier. First, the simulator reads in tool positions, tool orientations, and drill status information from a raw data file. Then, the simulator applies these position and orientation values to the tutor's tool, line by line in each simulation loop, making the tool move automatically as previously recorded. If the read-in drill status is on, the tutor's tool starts drilling, and if a collision with the tooth is detected, the tooth is cut. Meanwhile, the student could control the student tool by moving a haptic device stylus. The student's tool can move around freely in this training mode without collision detection or tooth interaction. The student need not worry about tooth cutting yet as that is taken care of by the replayed tutor's tool. Thus, the focus is only on catching up and superimposing the student tool on the tutor tool as the simulation is replayed. The simulator also provides a *conditional replay* option which, once enabled, will replay the tutor's trajectory only if the student's tool is close enough

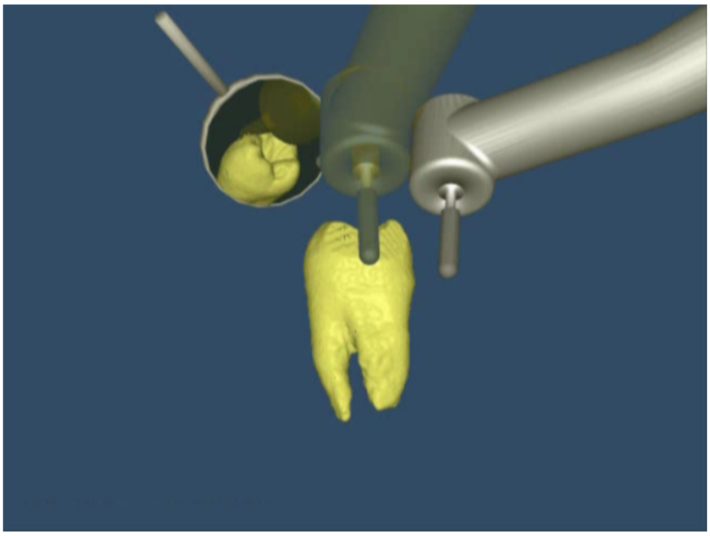


Figure 5.13: A tutor's tool (dark grey) and a student's tool (light grey) are shown on the same screen in training Mode 3. The tutor's tool is replayed while the student's tool is controlled by a student. The tooth is cut by the tutor's tool only.

to the tutor's tool in terms of position

$$\|\Delta \boldsymbol{X}\| < \varepsilon \tag{5.1}$$

as well as orientation around all axes

$$\begin{aligned} &\|\Delta\omega_x\| < \theta_1, \\ &\|\Delta\omega_y\| < \theta_2, \\ &\|\Delta\omega_x\| < \theta_3 \end{aligned} \tag{5.2}$$

where $\varepsilon, \theta_1, \theta_2, \theta_3$ are adjustable threshold values. This conditional replay option would help a novice who initially has trouble keeping up with the actual pace of the tutor's replay. An advanced student could turn this option off to experience the actual speed used by an instructor in producing the trajectory (Figure 5.14).

While the implementation of this active training mode is quite straightforward, its impact on student learning experience and training effectiveness could be high. The reason is that superimposing a tool onto a tutor's tool in *real-time* is probably the most intuitive way to imitate a tutor's performance. However, traditional training methods only allow a student to practice *after* observing an instructor's performance, obviously due to physical restriction.

Mode 4: Experiencing correct force sensation

All of the training modes described earlier aim to explore the visual features of a dental operation and to provide an environment for a student to practice hand-eye coordination and trajectory learning. However, a dental procedure cannot be successfully performed without a well-developed sense of touch and fine motor skill. Therefore, students also need proficiency in force sensations. Unfortunately, it is generally agreed that this is the most difficult part of skill training.

With conventional training methods, dental instructors find it challenging to transfer force sensation skill to students. The reason is that these training methods do not allow a student to experience

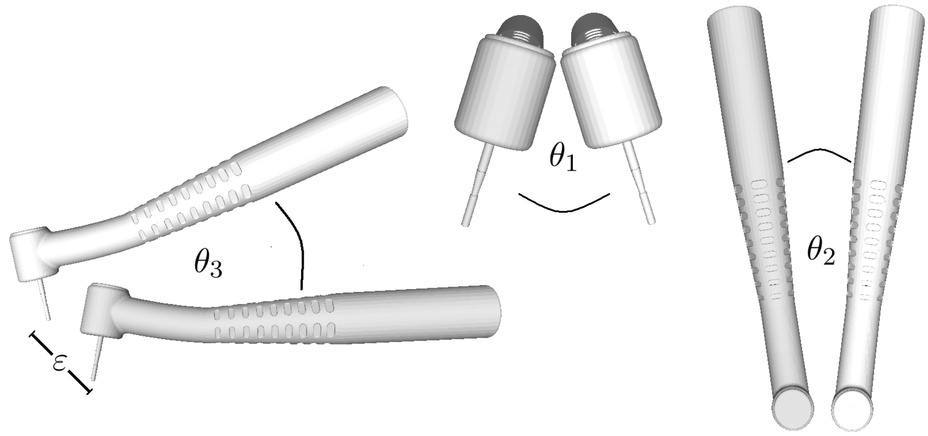


Figure 5.14: With conditional replay, a leading instructor's tool will progress only if a student's tool is following closely within ε units for position and $\theta_1, \theta_2, \theta_3$ units for orientation.

exactly how each step in a dental procedure should feel (Steinberg et al., 2007). While visual dental features can be described verbally or demonstrated through video, tactile sensation is very difficult to explain. For example, in Section 5.1, after receiving verbal feedback on applied force such as *"...force should be 2 times higher...,"* students might be unsure about how to improve their performance. This is because students, especially novices, are sometimes unable to judge their own effort during the operation.

Training Mode 4 aims to help students experience correct force sensation. With a haptic device, it is possible to capture tactile sensations during a dental procedure and replay them for a student to feel what an instructor felt in the process. In contrast with Mode 2 in which a student is passively guided through a trajectory without experiencing the forces exerted by the instructor, this mode is a *proactive* method for tactile skill training in which a student must apply the proper amount of force to follow the instructor's trajectory. In other words, a student's hand is *dragged* in Mode 2, while it has to *actively exert* the proper amount of force by itself in Mode 4.

To achieve this, we investigated a proactive tactile training method proposed by Saga et al. (Saga, Kawakami, & Tachi, 2005; Saga, Vlack, Kajimoto, & Tachi, 2005) in their haptic skill transfer system. With this technique, the amount of force applied by the instructor during the recorded procedure are rendered to the haptic device but in the opposite directions. Therefore, while a student holding a haptic device stylus tries to follow the instructor's path, he/she has to apply the same amount of force in the original direction to cancel out the rendered opposite force and proceed in training. The method was evaluated and found to be effective in a letter writing task (Saga, Kawakami, & Tachi, 2005).

Figure 5.15 illustrates the idea of implementing this method in our VR simulator. In the figure, the instructor's tool movement is replayed and a student tries to learn the path by following the movement of the expert's tool. Since the instructor was touching the tooth surface with force $\boldsymbol{F}$, the force $\boldsymbol{F'}$ with the same magnitude but opposite direction is rendered to the student's stylus, pushing it away from the correct trajectory. In order to keep up with the instructor's movement as well as to stay on track, the student has to apply force $\boldsymbol{F}$, to cancel out the force $\boldsymbol{F'}$. With this technique, both the visual and haptic information from the instructor's session can be transferred to the student in a proactive manner. Note that a student can also enable the same *conditional replay* mode explained in Mode 3

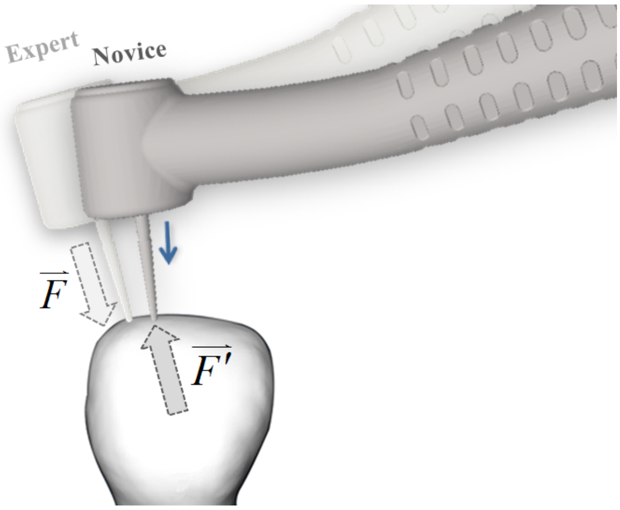


Figure 5.15: Path and force learning with visual and haptic information in training Mode 4.

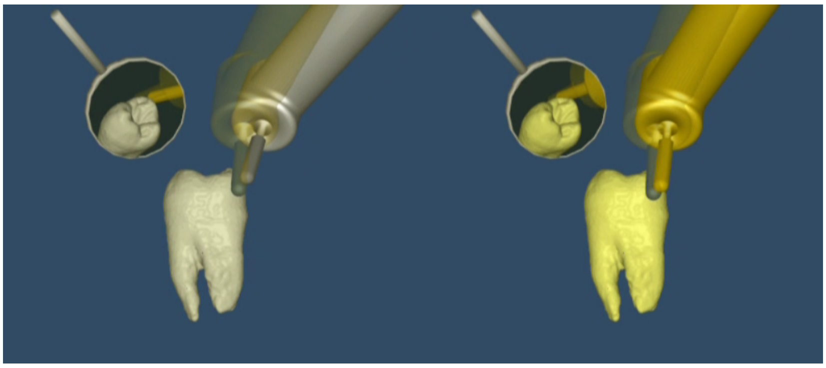


Figure 5.16: The overlayed instructor tool and tooth change color to provide a hint to a student training in Mode 5 to cut the tooth.

as well.

Mode 5: Manual operation with expert visual overlay

This mode is quite similar to the actual practice session where students perform a procedure by themselves. The only difference is that there is also an overlayed instructor tool being replayed for the student to follow.

Once a training session starts, the simulator merely replays the instructor's performance as an overlayed visual cue on the screen. The instructor's tool moves automatically on the previously recorded path and goes through the virtual tooth without colliding or cutting. During replay, the student tries to keep up with the instructor's overlayed tool by moving the haptic device stylus. The student has to cut the tooth if it comes in the way, haptically preventing the student's tool from penetration. To provide a hint to the student that cutting is needed at a particular position, the replayed tools and tooth will change color whenever the drill status in the replayed data is on (Figure 5.16). Students are suggested to activate the drill switch and start drilling whenever they observe color changes.

After mastering this training mode, a student must have experienced correct hand-eye coordination and acquired the proper force sensations needed to perform the dental procedure. The student should have confidence in the particular dental procedure since he or she could perform it the same way the instructor did previously.

5.4 Discussion

We have presented various technique to enhance our VR dental training simulator so that it could serve as an intelligent, autonomous, virtual instructor in dental skills.

We first explained our technique to generate training feedback based on statistical comparison between student and instructor dental operational features. An experienced instructor generally agreed with the training feedback generated by the simulator at each procedure stage. However, our system uses the manually specified stage labels to generate tutoring feedback messages for each stage. Strategies for automatic stage segmentation will be investigated in future work. Other limitations of the feedback generation experiment include the simplistic nature of the crown preparation procedure and the condition that students need to perform the procedure with pre-specified steps and orders.

We also investigated the role of several variations of augmented kinematic feedback on dental skill acquisition. In dentistry, as well as many learning settings, the most effective kinematic patterns are generally known to the instructors. The instructors typically provide kinematic feedback to bring student patterns in line with these optima. The strength of a VR training simulator is that it can automatically record associated kinematic data on how students or instructors perform each step of the task, e.g., instrument positions, force, and mirror view used, which are not available in the conventional skill training environments. In our study, various augmented feedback variables were provided to examine their influence on learning. Overall, each of the augmented kinematic feedback variables appeared to be effective in the acquisition phase. This finding agrees with previous research showing that kinematic variables can serve as information feedback to enhance performance in acquisition (Bilodeau, 1966; Feil et al., 1986). Moreover, all three kinematic feedback variables led to enhanced performance over the KR-only group in the retention test in which kinematic feedback was not given. The novice users in this study demonstrated an increase in outcome scores at the end of the training sessions. This trend is consistent with the results of the study conducted by Wierinck et al. (2007)

Finally, we have introduced various training modes to facilitate smooth transfer of dental motor skills from instructors to students. The training modes range from merely observing to actively engaging. Performance observation with our interactive replay mode has many advantages over watching training videos. However, it currently allows only one performance to be replayed at a time, either an instructor's or a student's. We are investigating a technique to simultaneously visualize the motion of instructors and students with varying speed in a synchronized manner using dynamic time warping (DTW) as proposed by Sielhorst et al. (2005) and Blum et al. (2007). Other training modes require more student involvement by holding or controlling a haptic device stylus. These modes vary from passive learning through hand guidance to more challenging modes where fewer hints are provided. These techniques have been implemented and tested in close collaboration with experienced dental instructors. However, a thorough study on the effectiveness of these training strategies in dental skill transfer is still needed. We plan to design and conduct experiments to investigate the role of each training mode on dental skill acquisition and retention performance in both the VR environment and the actual clinical setting. The effective training modes could be integrated into the final system as they have potential to reduce difficulty and enhance the learning experience. The positive results could also help improve the acceptance of VR training for skills and problem-solving in dentistry.

Chapter 6

Conclusions and Recommendations

Conclusions

Dental education is a discipline that could especially benefit from haptic VR simulation since a significant proportion of the training is dedicated to teaching clinical psychomotor skills. Recently, many research groups have attempted to build 3D databases of human teeth in diverse conditions (Nagasawa et al., 2010; Abdelmunim et al., 2011; Yoshida et al., 2011). This could be useful in various aspects of dental education including the use of tooth data in VR simulators such as ours. In this dissertation, we designed and implemented realistic VR dental training simulators and demonstrated the positive impact they have had on the acquisition and retention of dental skills. Overall, the contributions of our work are two-fold. First, we have developed dental training simulators to perform virtual procedures in the presence of visual and tactile feedback. The simulators have been validated as adequately realistic and have been deemed useful in practicing dental operations. We have also demonstrated the transferability of learnt skills from VR to physical settings. Second, we have integrated intelligent performance assessment and tutoring modules that track student progress, provide tutoring feedback, and teach complex motor skills. Many of the techniques and strategies we have developed should generalize well to other dental or medical procedures. The graphics and haptic rendering algorithms could be directly applied to drilling, cutting, and sculpting simulation of solid materials such as temporal bone, skull, wax, and metal. Soft deformable parts, however, would require different algorithms. The performance assessment and tutoring strategies could also be applied to various tasks requiring fine motor skills such as suturing and calligraphy.

We began with the goal to develop a VR dental simulator from scratch so that we could achieve an acceptable level of realism and so that we could access all low-level simulation data. We started with limited knowledge in advanced real-time computer graphics and haptics. For this reason, the first haptic VR simulator for crown preparation training based on triangle mesh models took around two years to develop. However, it was encouraging that dental students found that the simulator provides a realistic environment useful in dental practice. Based on their feedback, we improved the simulator by introducing the volumetric approach for data representation and haptic rendering. This more sophisticated simulator eliminates most of the limitations of the first and enables a greater variety of dental procedures to simulate. We have also demonstrated that training with the simulator results in improved performance in the physical setting.

On the attempt to make the simulator an intelligent tool for self learning of dental skills, we have introduced various measures to reduce the need for instructors to guide students during simulation sessions. First, we describe a mechanism for providing objective skill assessment. The simulator is able to classify the performance of a particular operator as novice-level or expert-level with high accuracy based on recorded process-related data using a hidden Markov model. Second, the simulator can generate objective tutoring feedback with quality comparable to that of human tutors by comparing student and expert process data. Third, we investigate the potential of several variations on automatic tutoring feedback to bring student movement patterns in line with optimal patterns. We empirically evaluated the influence of the feedback on skill acquisition. We found that each of the augmented kinematic feedback variables appear to be effective. Finally, we discussed various motor skill training modes in varying difficulty levels to help transfer skills from instructors to students effectively.

The results of most of our evaluation studies have been extremely promising, proving the applicability of our VR dental training simulator as a supplemental training tool for dental surgical skills. The dental VR simulator provides a platform for investigating many interesting issues in the area of psychomotor skills in dentistry. Next, we outline a few of the promising areas for future research.

Recommendations

To reduce the difficulties faced by dentists in familiarizing themselves with the VR dental training simulator, we could adjust the physical setting of our simulator to match with those in the conventional trainings. The first thing to consider is using a 3D model of the whole mouth or even the entire human head model just like a dental phantom head. However, this would involve sophisticated graphic and haptic rendering of soft tissue (gingiva, tongue, skin) deformation. A number of recent studies on VR simulation in medicine have proposed graphics and haptics techniques to solve this problem (Peterlík, Nouicer, Duriez, Cotin, & Kheddar, 2011; Barbic & James, 2008; Lim & De, 2007; Sela et al., 2007; J. Kim, 2004) but no applications in dentistry exist. Second, sophisticated surgical procedures would require six degree of freedom (6-DoF) haptic hardware and rendering algorithms for realistic physical interactions such as torque. However, the cost of 6-DoF devices makes them impractical for use on a large scale. Realistic 6-DoF haptic rendering is still an active research area (Chan, Conti, Blevins, & Salisbury, 2011; Barbic & James, 2008; Otaduy & Lin, 2006b). Furthermore, synthetic contact sounds based on physical properties such as tooth hardness and instrument drill speed are also recommended by experts to enhance realism. Finally, a co-located environment that resembles hand-eye coordination experience in a physical training should be investigated. To achieve this, we describe our preliminary study on Augmented Reality (AR) for co-located simulation in Appendix A.

Regarding the intelligent aspects of our simulator, there are some enhancements to be explored. For dental performance assessment with HMMs, the number of subjects in our study was relatively small. Experiments with more participants and various skill levels should be conducted. We also assumed and verified that each participant followed all procedure stages in the correct order. However, advanced students might perform a procedure in a different direction or omit some procedure stages. We will certainly need more sophisticated reasoning as we move to more challenging tutoring scenarios with more advanced students. Moreover, advanced 3D image processing techniques for shape matching might be used to automatically assess dental performance based on 3D tooth outcome of a procedure. Finally, the motor skill training strategies that we proposed require thorough evaluations with moderately complex procedures involving complicated pathways. Another feature that could make these training strategies even more useful is a framework that allows experts to add annotations to important sections of recorded performances.

Appendix A

Augmented Reality Haptics System for Dental Skills Training

There are many benefits of VR training simulators which are invaluable and cannot be realized through the conventional training on phantom head or live patients. However, one issue with VR simulators is that they are not co-located; users have to look at the monitor screen instead of their hands during an operation (see Figure A.1). This makes hand-eye coordination quite difficult for beginners and results in unrealistic simulation. Thus, eventually, skills acquired from these simulators are not guaranteed to transfer to the physical setting in the operating room.

In this section, we propose a solution to this problem. Based on the volumetric VR dental training simulator described in Chapter 2, we explain techniques to transform the VR environment into a co-located augmented reality (AR) environment. We also discuss the results of a preliminary evaluation with real users.

A.1 Augmented Reality Enhanced Simulator

While virtual reality replaces the real world with a simulated environment, augmented reality tries to bring the real and simulated worlds together. AR provides a live view of a physical environment and augments it with computer-generated data within a single display. According to the reality-virtuality continuum proposed by Milgram and Kishino (1994) (see Figure A.2), AR is mostly grounded in the real environment, with a limited set of objects from the virtual environment mixed in.

Within an AR training environment, a user can see his or her real hands holding a virtual instrument working on virtual objects within a physical setting. This co-located setup is an advantage of AR over VR as it makes hand-eye coordination during a simulated operation easier. Therefore, AR also has the potential to improve the realism of the simulator and to ensure transfer of skills acquired.

One common technique for co-located AR displays relies on a CRT monitors and a translucent mirror (half-mirror); this kind of setup is relatively large and requires additional hardware and software for head tracking. An example of such setup is shown in Figure A.3.

We transformed our VR dental simulator into an AR environment using a video see-through head-mounted display (HMD) with a camera attached at the front (see Figure A.4). Figure A.5 (right) shows an example of an image displayed on the HMD screen. The registration of the 3D tooth in the actual environment is realized by ARToolKit[1] (Kato, Billinghurst, Poupyrev, Imamoto, & Tachibana, 2000), an open source AR library.

Within this AR environment, the haptic device is co-located with the 3D graphics, giving users a

[1] Available at http://www.hitl.washington.edu/artoolkit/

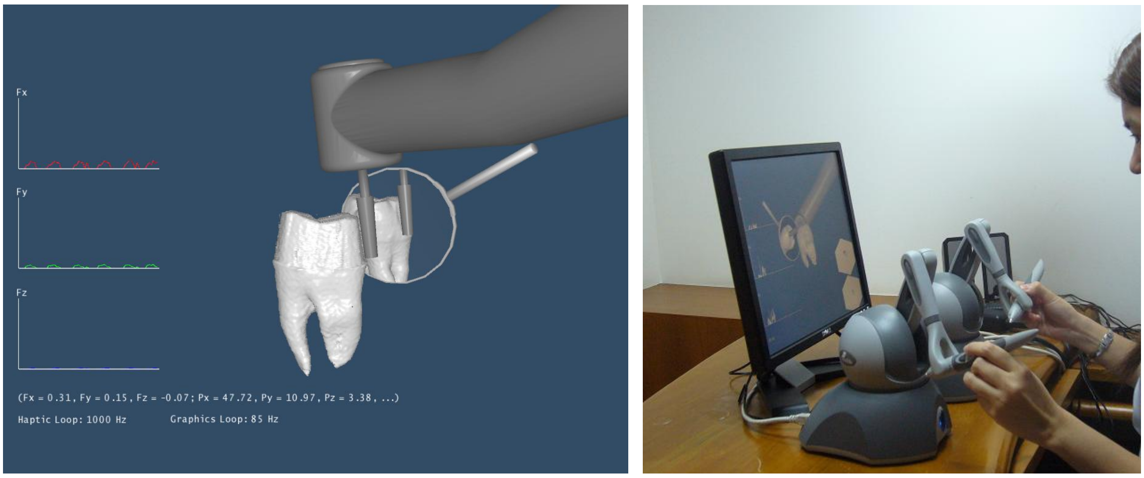


Figure A.1: Screenshot (left) and setup (right) of the VR dental simulator with dual haptic configuration. An optional second haptic device is used to control the virtual dental mirror.

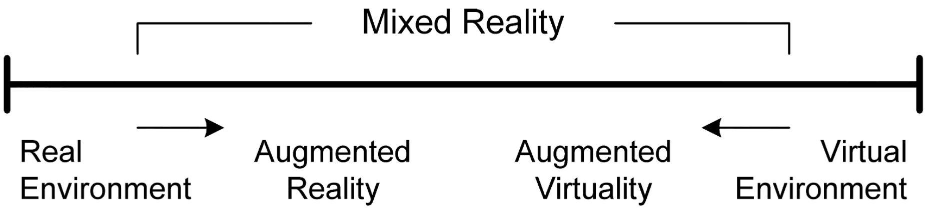


Figure A.2: Milgram's reality-virtuality continuum (Milgram & Kishino, 1994).

more natural way to practice dental surgery, in which hand-eye coordination is crucial. Real-time head tracking is made possible by continuously grabbing camera images, detecting AR markers, and registering the 3D tooth accordingly. By attaching another AR marker to a real dental mirror, as shown in Figure A.5 (left), we can register the virtual mirror and render reflections onto it. A similar idea using retroreflective fiducial markers for intra operative visualization and navigation has been implemented by Bichlmeier et al. (Bichlmeier et al., 2009). Besides increasing the realism of the simulation, this technique also eliminates the need for a second haptic device to control the virtual mirror.

A.2 Preliminary Evaluation

In previous work, we asked dental students and a dental instructor to evaluate the VR system in the context of a tooth preparation procedure. The users found the realism of the VR system's graphical and haptic rendering to be acceptable, but some evaluators found it difficult to navigate and control the dental tool in the simulator. Participants also added that the practice session should have been

Figure A.3: Co-located AR displays with a CRT monitors and a half-mirror (photo courtesy of Uppsala University).

Figure A.4: Vuzix iWear VR920 head-mounted display with iWear CamAR monocular camera (see www.vuzix.com).

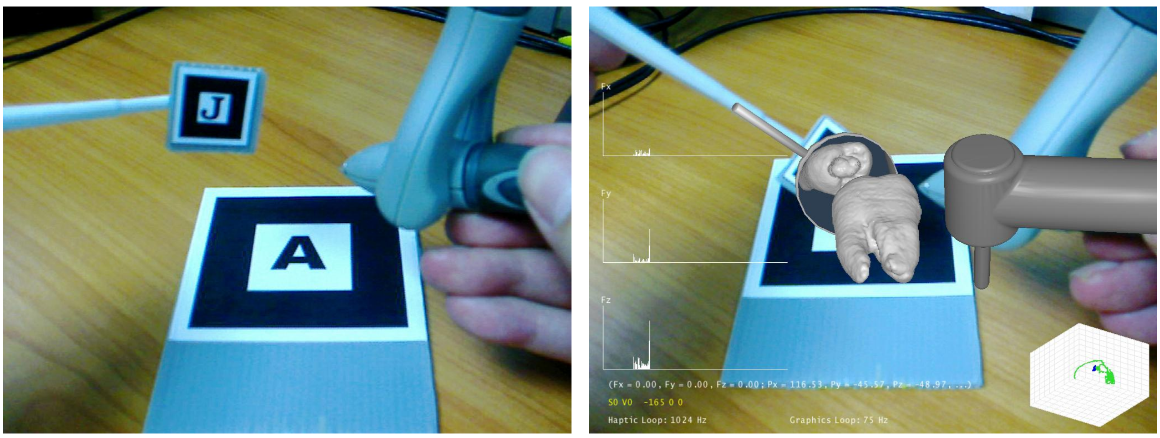


Figure A.5: A grabbed image from the camera (left) and the augmented reality scene displayed in the HMD screen (right).

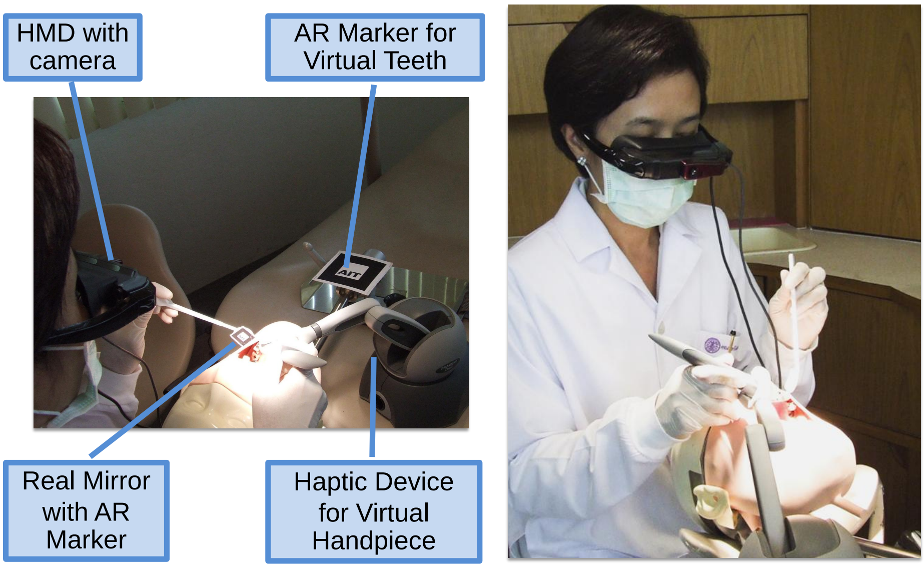


Figure A.6: An ideal AR environment resembling a real clinical setting.

Figure A.7: Occlusion problem (left) and expected outcome (right).

longer, as they needed more time to familiarize themselves with the simulator to the point that they could demonstrate their true surgical skills. We attribute these problems to the difficulty of hand-eye coordination in non co-located VR systems.

On completion of the AR prototype, we asked a dental instructor from a Faculty of Dentistry to give a preliminary evaluation of the new approach in the context of crown preparation and a pulp access opening operations. The expert agreed that the new environment is much closer to a real clinical setting. She also suggested an ideal setting in which the virtual tooth is overlaid on a traditional mannequin along with other tangible real teeth. Figure A.6 shows this ideal setting. We could achieve this, but occlusion problems, in which real objects are occluded by virtual objects regardless of relative depth, must be solved; see Figure A.7 (left). One solution is to construct a visual hull surface of a phantom model, as described by Fischer et al. (2004). The expected outcome after applying this technique is shown in Figure A.7 (right).

A.3 Discussion

We have given an overview of our AR dental training simulators. As expected by us and confirmed by an experienced dentist, there are many advantages of the AR approach over the VR approach to dental surgical simulation. The co-located visuo-haptic display in the AR environment is closer to the actual clinical setting. This resemblance should reduce the time necessary for users to familiarize themselves with the system, and their performance in the simulator should better reflect the true dental surgical skill. As a result, skills acquired using the simulator should transfer well to the operating room.

There are a few concerns regarding the use of a video see-trough HMD. First, the experienced dentist who evaluated the system feels that the HMD is rather heavy for long-lasting simulation sessions. However, all of the procedures we currently simulate can be completed in approximately two minutes by an expert and five minutes by a novice, so the weight is acceptable for these short periods. Another issue is that users' depth perception is limited by the use of a monocular camera. Accurate depth perception is very important in dental surgery, and stereo cameras would improve users' sense of depth dramatically. For the time being, HMDs with stereo cameras are prohibitively expensive, but manufacturers have already announced plans to launch less expensive products soon. Finally, the resolution is limited by the camera's specifications. However, compared to other solutions for co-located visuo-haptic system such as a half-mirror, HMDs are still our preferred technique, due to their mobility and performance, as also confirmed by Sandor et al. (2007).

For future improvements, we plan to combine the current setup with a phantom head with real teeth as suggested by the expert for better realism. We will also consider utilizing a stereo HMD for better depth perception. Finally, alternatives to ARToolKit's fiducial markers, such as retroreflective or natural feature tracking, will be explored.

Appendix B

List of Publications

Journal Publications

- **Intelligent Dental Training Simulator with Objective Skill Assessment and Feedback**
  Rhienmora, P., Haddawy, P., Suebnukarn, S., Dailey, M. N.
  Artificial Intelligence in Medicine, 52(2), 2011
  Publisher: Elsevier

- **A Virtual Reality Simulator for Teaching and Evaluating Dental Procedures**
  Rhienmora, P., Haddawy, P., Khanal, P., Suebnukarn, S., Dailey, M. N.
  Methods of Information in Medicine, 49(4), 2010
  Publisher: Schattauer

- **Development of a Dental Skills Training Simulator Using Virtual Reality and Haptic Device**
  Rhienmora, P., Haddawy, P., Dailey, M. N., Khanal, P., Suebnukarn, S
  NECTEC Technical Journal, 8(20), 2008
  Publisher: National Electronics and Computer Technology Center

- **Access Cavity Preparation Training Using Haptic Virtual Reality and Microcomputed Tomography Tooth Models**
  Suebnukarn, S., Hataidechadusadee, R., Suwannasri, N., Suprasert, N., Rhienmora, P., Haddawy, P.
  International Endodontic Journal, 44(11), 2011
  Publisher: Wiley-Blackwell

- **Augmented Kinematic Feedback from Haptic Virtual Reality for Dental Skill Acquisition**
  Suebnukarn, S., Haddawy, P., Rhienmora, P., Jittimanee, P., Viratket, P.
  Journal of Dental Education, 74(12), 2010
  Publisher: The American Dental Education Association

- **Process and Outcome Measures of Expert/Novice Performance on a Haptic Virtual Reality System**
  Suebnukarn, S., Phattanasatheinkul, N., Sombatveroj, S., Rhienmora, P., Haddawy, P.
  Journal of Dentistry, 37(9), 2009
  Publisher: Elsevier

- **Haptic Virtual Reality for Skill Acquisition in Endodontics**
  Suebnukarn, S., Haddawy, P., Rhienmora, P., Gajananan, K.
  Journal of Endodontics, 36(1), 2009
  Publisher: The American Association of Endodontists

Conference Publications

- **Providing Objective Feedback on Skill Assessment in a Dental Surgical Training Simulator**
  Rhienmora, P., Haddawy, P., Suebnukarn, S., Dailey, M.N.
  In *Proceedings of the 12th Conference on Artificial Intelligence in Medicine (AIME 2009)*, Verona, Italy
- **Augmented Reality Haptics System for Dental Surgical Skills Training**
  Rhienmora, P., Gajananan, K., Haddawy, P., Dailey, M.N., Suebnukarn, S.
  In *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology (VRST 2010)*, Hong Kong, China
- **A VR Environment for Assessing Dental Surgical Expertise**
  Rhienmora, P., Haddawy, P., Suebnukarn, S., Dailey, M.N.
  In *Proceedings of the 14th International Conference on Artificial Intelligence in Education (AIED 2009)*, Brighton, UK
- **Haptic Augmented Reality Dental Trainer with Automatic Performance Assessment**
  Rhienmora, P., Gajananan, K., Haddawy, P., Suebnukarn, S., Dailey, M.N., Supataratarn, E., Shrestha, P.
  In *Proceedings of the 14th International Conference on Intelligent User Interfaces (IUI 2010)*, Hong Kong, China

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