Development of a Virtual Reality Force Feedback-Enabled
Dental Drill Training Simulation

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Abstract: Effective diagnostic capabilities and good drilling technique are both vital skills for dentists. Typical training approaches include the use of synthetic replica teeth or real teeth extracted from patients. Both present challenges with respect to cost and difficulty of creating representations of specific pathologies. Our research focuses on developing interactive computer-based simulations to help address these issues. We have created a prototype dental drilling training system that demonstrates a number of key technical components, and we have begun the process of validating the educational effectiveness of the simulator by running a pilot user study. The aim of the pilot study is to evaluate our experimental design and to identify potential improvements to the system design and experimental procedure in preparation for a full-sized user study. Method: We have run a user study in which we compared the performance of simulator-trained students to that of students trained using real-world drills. All participants were first or second year undergraduate dental students at Fukuoka Dental College with no prior experience in dental drilling. Results: Over the course of multiple training sessions, practice time decreased sharply for participants in the real-world training group, while it increased for those in the simulation group, indicating increased engagement with the task in the simulation group. Participants in the simulation group also showed a large jump in performance after the first session. This jump can be attributed to participants overcoming their initial unfamiliarity with the virtual reality system. Performance of the two groups on the final test was very close. Conclusion: The results of the experiment are encouraging, in that the simulation group experienced no recognizable negative training effects and performed on par or better than the real-world training group. The pilot study also pointed out a number of areas for improvement in the simulation, such as a more intuitive display system and better replication of the true hardness of teeth within the simulation, which we have since incorporated into the program. We will begin a modified and expanded version of the same study based on the experience gained from the pilot study.

Keywords Virtual Reality, Haptic Simulation, Dental Drill Training, Force-Feedback Device

1. Introduction

Effective diagnostic capabilities and good drilling technique are both vital skills for dentists. Dental students typically learn these skills through a combination of practice on replicas of human teeth and supervised training on patients. However, it is difficult to create replicas that model specific pathologies, and the costs of replicas can quickly escalate if repeated practice is required. In addition, practicing on patients always introduces the risk of potentially dangerous mishaps during the procedure and gives the instructor little control over the types of pathologies on which a student practices. Our research focuses on developing interactive computer-based simulations to help address these challenges. We have created a prototype dental drilling training system that demonstrates a number of key technical components, and we have begun the process of
validating the educational effectiveness of the simulator by running a pilot user study.

Many surgical disciplines face challenges similar to those present in dental education. These challenges have spurred the creation of multidisciplinary research efforts to develop computer-based training tools that augment and enhance medical training. Projects cover a wide range of applications from computer-generated visualizations of anatomy that aid in learning spatial relationships between different structures to interactive surgical simulations that attempt to replicate the key components of various surgical procedures. In particular, force feedback-enabled simulations have garnered much recent interest. These are simulations that use special interface devices to allow a user not only to see, but also to feel what it is like to perform a surgical procedure. For example, a program might display a graphical representation of a liver that a user can actually touch and cut into using a force feedback interface device. Within the field of dental education, a variety of projects have sought to apply computer technology to the training of dental surgery skills.

However, as yet, none have provided a compelling mix of features in a system that is easy to use and easy to integrate into an existing curriculum. At present, the most widely used dental surgery simulator is the DentSim system from DenX Ltd.[1-3]. When using the system, a student utilizes a real drill to carve a synthetic tooth. The system is ergonomically correct and automatically evaluates the student’s performance by tracking the motions of the user’s hands and by using computer vision algorithms to create and measure a 3D reconstruction of the test object on which the student practices. However, the system requires large investments of time, money, and space, and it provides only limited haptic response, since the teeth being drilled are uniform synthetic objects whose material properties are difficult, if not impossible, to alter.

Research has shown that even straight-forward virtual reality-based visualization programs that allow students to interactively view three-dimensional models of anatomical structures have a positive impact on student performance[4]. In addition, computer-based surgical simulations have shown significant training benefits in other fields, like laparoscopy[5,6]. Other research groups have designed fully computerized dental drilling simulators, but these systems have generally provided unconvincing force feedback and incomplete integration within the traditional dental education curriculum[7]. Findings like these led us to design our system for dental drill training.

The simulation accurately reproduces the drilling experience in a computer-generated environment allowing for easy repetition, performance evaluation, and representation of a wide range of anatomical and pathological variations. In order to evaluate the effectiveness of the simulator, we must devise a user study that will quantify the impact of the system on student performance of a dental drilling task. The aim of the present pilot study is to evaluate our experimental design and to identify potential improvements to the system design and experimental procedure in preparation for a full-sized user study.

2. Method

2.1 Simulation System

Our prototype simulation uses a standard computer monitor or a head-mounted display (HMD) to present a user with a view of a set of teeth. The system uses a force-feedback device, the SenseAble, Inc. PHANTOM Omni, as the primary input device, along with a USB foot pedal to turn the virtual drill on and off. The hardware setup is shown in figure 1.

The user holds the stylus of the PHANTOM as if it is the shaft of a dental drill. Movements of the stylus control the motion of a virtual drill shown on the monitor.
Fig. 2: The virtual teeth are modeled as volumetric objects consisting of thousands of small cubic elements, called voxels.

or HMD. The virtual drill can be brought into contact with the virtual teeth, and the force-feedback device generates forces that simulate contact between the two. The virtual drill can also be used to drill into the teeth from any direction with realistic reaction forces.

The user can change the view of the scene by moving the mouse or, if using the HMD, by moving his or her head. The view can be zoomed in and out and rotated freely. In addition, the tip of the drill can be set to be translucent during drilling in order to improve the user’s view of the area being drilled.

The virtual teeth are modeled as volumetric objects consisting of thousands of small cubic elements, called voxels, as shown in figure 2.

The models used in the prototype have been created by first hand segmenting cone-beam computed tomography (3DX multi-image micro CT, Morita Co.) scans of real teeth to create polygonal surface models. The process is summarized in figure 3. Within each tooth, the enamel, dentine, and dental pulp have been individually identified, and as described below, each of these layers has a different feel within the simulation just as in the real world.

2.2 Force Feedback

The force feedback device that serves as the interface to the program and applies forces to the user’s hand is a motorized, articulated arm. The program controls motors within the device that stiffen or loosen the joints in the arm in order to prevent or allow movement in different directions. In order to mimic the feel of a dental drill being used on real teeth, the simulation must compute the amount of force to transmit through the force feedback device to the user’s hand. In the simplest case, when the drill is not active, the program must apply enough force to prevent the tip of the virtual drill from penetrating the teeth. However, when the drill is active, the bit slowly removes material from the tooth being drilled, so the force profile is more complex. Our force feedback algorithm takes advantage of the voxel representation used for the teeth models. Building on earlier work on haptic modeling of drill mechanics, we have developed a technique that incorporates added filtering and an optimized force computation to produce a smooth and consistent force response[8-12]. As shown in figure 4, the system computes the intersections between the voxels representing the drill and those representing the teeth.

Each intersection generates a force directed toward the surface of the model. The total force is the vector sum of these intersection forces.

Each voxel in a tooth model has an associated density that is used to weight the force computed for a drill point that falls within the voxel. When the drill motor is active, a voxel’s density value is reduced during every

Fig. 3: The three dimensional images of dentition data were acquired by cone-beam computed tomography (3DX multi-image micro CT, Morita Co.). The 3D model has three layers, enamel, dentine and dental.

Fig. 4: The system computes the intersections between the voxels representing the drill and those representing the teeth and creates a force response based on the number and locations.
frame update in which the drill bit is in contact with that voxel. Once the density reaches zero, the voxel is removed from the model. Thus, by increasing or decreasing these density values for different regions of a model, we can make those regions feel harder or softer, since a higher density voxel takes longer to drill through and thus feels harder than a lower density voxel. In particular, the software models the differences in hardness between the enamel, dentine, and dental pulp layers by assigning different density values to each of the layers.

The dental drill also affects the rate at which material is removed. In order to model different types of drills, we assign a drill speed to each drill. The speed value controls the amount of tooth voxel density that the drill removes during one force update frame, with a higher-speed drill removing more material per frame and, thus, feeling as if it passes more smoothly through a tooth than a lower-speed drill.

2.3 Experimental Design

In order to begin to understand the impact of using the simulator on student performance, we have run a small pilot study in which we compared the performance of simulator-trained students to that of students trained using real-world drills. The experiment consisted of three groups of participants with 6 participants in the group that received simulator-based training, 5 in the group trained using real drills (Air bearing handpiece Astron a 2 ((SAT-C2)) from J. MORITA MFG Corp., and 5 in a control group that received no training. The simulation group used an early version of the training program that provided only a monitor-based display option. The HMD option was added as a result of the pilot study. All participants were first or second year undergraduate dental students at Fukuoka Dental College with no prior experience in dental drilling. Participants in both training groups had five training sessions, with one session per day for five consecutive days. In the case of the simulation training group, participants used the program to drill away the red area of the test object shown in figure 5-A. Participants in the real-world training group practiced on similar real objects, as shown in figure 5-B.

Before the first training session, each participant was given a brief presentation describing the experiment, the controls for the drill, and the goal of the exercise, i.e. to drill away the red colored region while leaving the white region intact. Both the real and virtual objects measured 15 mm by 15 mm by 40 mm, and the red drill area was 2.5 mm deep in both cases. The hardness of the virtual test object was set to be as close as possible to that of the real test object, which was made of gypsum. For each training session, participants in both groups were allowed to practice until they felt comfortable with their results. The total time taken by each participant was recorded for each practice session.

On the sixth day after training began, all participants were asked to drill away the red area from real test objects of the same size as the training objects. The configuration of the test objects was as shown in figure 6. Again, observers recorded the total time taken by each participant. After participants completed the final test,
they were asked to fill out the exit survey shown in table 1.

Table 1. Exit survey. Only participants in the VR training group answered the last question.

1. Do you think that drilling is a necessary skill for dentists?
   Answers choices: quite unnecessary, unnecessary, don't understand, necessary, very necessary.
2. Is it possible to use the simulator to practice drilling?
   Answers choices: absolutely no possibility, unlikely, don't understand, some possibility, definitely.
3. How do you think the feel of a real drill compares to that of a virtual drill?
   Answers choices: very different, somewhat different, don't understand, somewhat similar, very similar.
4. How many practice sessions did it take you to become accustomed to the virtual simulator?

At the conclusion of testing, the drilled test objects were evaluated for drilling quality independently by three different dental experts. Each reviewer examined all of the drilled objects from the final test. The reviewers viewed the test objects in random order and did not know which participant carved each object. Figure 7 shows the evaluation sheet used by the reviewers to score each test object.

The scores were based on accuracy of the overall carved shape, smoothness of the vertical and horizontal surfaces, drill depth, and overall uniformity of drilling. The reviewers assigned a score from 0 to 10 for each criterion, with 0 being the worst score and 10 being the best, and a reviewer's total score for an object was computed to be the sum of the individual criteria scores.

For each participant, the final score was computed as the average of the three scores from the different reviewers.

3. Results

Figure 8 shows the average duration of each training session for the two training groups. As can be seen, practice time decreased sharply for participants in the real-world training group, while it increased for those in the simulation group. Based on conversations with participants and observations during training, we theorize that this difference is due in part to participants in the simulation group finding their task more engaging and less intimidating than those in the real-world group. As shown in figure 9, participants in the simulation group showed a large jump in performance after the first session. This jump can be attributed to participants overcoming their initial unfamiliarity with the virtual reality system. In particular, questionnaire responses indicated that using a monitor for display and a mouse to control the viewpoint proved to be a counter-intuitive interface that required significant effort to learn to control. Once they became comfortable with the computer system, participants made steady improvements in performance.

![Fig. 7: The evaluation sheet used by the reviewers to score each test object. Each criterion was scored on a scale from 0 to 10.](image)

![Fig. 8: Average duration of training sessions for simulation and real-world training groups.](image)

![Fig. 9: Average score for each training session for both groups.](image)
The real-world training group exhibited a similar initial jump in performance due to gaining familiarity with the drill, but its impact on performance was much smaller than in the simulation group. The average final scores were as follows: the simulation training group averaged 24.5; the real-world training group averaged 21.5, and the control group that did not receive any training scored 20.4 on average. The simulation training group showed a higher final score than the other two groups. However, owing to the small sample size, this difference was found not to be statistically significant.

4. Discussion

As mentioned above, based on feedback from the participants in the simulation training group, we determined that the simulator must provide a more intuitive display and view control system than the standard monitor and mouse interface. Thus, we added an HMD mode that will be used in the full user study. We have also altered the force response of the simulation slightly in order to make the virtual test objects feel slightly harder and thus more closely match the feel of the real test objects. In addition, we have placed the force feedback device on a small raised platform on the desktop, so that users can rest their control hand on top of their opposite hand while drilling, which matches the typical hand positions used with real-world drills.

Overall, the results of the pilot study indicate that the training simulation holds promise for improving student training. For the full-scale user study, we will extend the training time to three weeks and include 50 participants. These extensions should give a clear picture of the impact of the simulation on drilling performance.

In the longer term, we will work to enhance the functionality of the simulator in a number of ways. For example, we are developing an automated evaluation subsystem that continually monitors student performance during a training session. The evaluation mechanism is based on an adaptive procedural model that can recognize errors in real time and, if desired, provide suggestions for improving technique. The evaluation system will also provide a critique of a student’s performance after a training session. In addition, we are creating an online database of 3D teeth models and medical imaging data reflecting a wide range of anatomical variations and pathologies. The next version of the simulation will be able to access this library to download models and present training scenarios tailored to a variety of different clinical situations.

Reference


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