Computer Methods and Programs in Biomedicine 64 (2001) 53–64

Computer Methods and Programs in Biomedicine

www.elsevier.com/locate/cmpb

The design and testing of a force feedback dental simulator

Geb Thomas [b,*], Lynn Johnson [a], Steven Dow [b], Clark Stanford [a]

[a] The College of Dentistry, The University of Iowa, Iowa City, IA 52242, USA

[b] The College of Engineering, Department of Industrial Engineering, The University of Iowa, Iowa City, IA 52242, USA

Received 17 May 1999; received in revised form 6 March 2000; accepted 31 March 2000

Abstract

The Iowa Dental Surgical Simulator is a haptic simulator to train dental students in the haptic skills of dentistry. The initial design emphasizes the detection of carious lesions. This work describes the software and implementation of the prototype system, the design tradeoffs' and the technical issues associated with haptic and graphics subsystems. The work also describes the current system performance, including a formal evaluation by practicing dentists and performance measures. A discussion of the limitations of the current system is followed by an analysis of opportunities to improve the quality of the simulator. The results should be of interest to designers of medical haptic simulation systems and other simulation designers. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Haptic feedback; Dental surgical simulators; Carious lesions

1. Introduction

1.1. The need for dental simulators

The Colleges of Dentistry and Engineering at the University of Iowa are collaborating to complete a prototype Iowa Dental Surgical Simulator (IDSS). The surgical simulator will be used to teach and evaluate the subtle tactile and surgical skills relevant to the dental profession. Currently, these skills are learned with live patients in an environment in which the student practices under the close supervision of an experienced dentist. Using live patients is time consuming and expensive, necessitating the supervisor to check each step of the student's work. Often there are significant waiting periods between the completion of each step. Haptic skills are particularly difficult to teach, because the supervising dentist must resort to interactions such as 'this area feels like a carious lesion. Do you feel that?' It is difficult to infer from the student's reply whether or not he or she understands and is using an appropriate amount of force on the explorer. The amount of applied force is important, but training with live patients affords the instructor no opportunity to evaluate the force the student applies. Since too much force can damage the tooth surface enamel, using the appropriate range of forces is an important skill in dentistry.

* Corresponding author. Tel.: +1-319-3355936; fax: +1-319-3355424.

E-mail address: geb-thomas@uiowa.edu (G. Thomas).

0169-2607/01/$ - see front matter © 2001 Elsevier Science Ireland Ltd. All rights reserved.
PII: S0169-2607(00)00089-4

The IDSS is designed to provide a more uniform educational experience and visual performance feedback for the student and instructor. This will assist students in gaining haptic skills and assist supervising faculty in verifying that the skills have been adequately learned. Several advantages offered by the simulator include: an effective learning environment without undue fear of mistakes, facilitation of repetition, control of training variation, provision of opportunities to quantitatively assess student skills, and avoidance of difficulties in recruiting willing subjects to serve as live patients. The simulator is expected to facilitate more rapid learning, but also to lower the costs of training dentists.

Although the IDSS will eventually be extended to a wide range of haptic tasks, the task presently implemented in the simulator is the detection of carious lesions (cavities) on the surface of teeth and within surgically cut dentin.

To detect carious lesions, dentists typically employ a combination of visual inspection and physical probing of the tooth surface with a sharp metal instrument. Although dental caries are often darker than healthy enamel, healthy enamel sometimes has a dark appearance. Also, some carious lesions may be the same color as the surrounding, healthy tooth surfaces. Consequently, physical probing is necessary to support the diagnosis of carious lesions. The sensation of probing less advanced carious lesions is often described as poking a leather surface with a sharp tool. For more advanced lesions the sensation is similar to poking soft cheese. The sensation involves resistance to motion into the tooth and also a characteristic tug when extracting the needle-like probe tip.

1.2. Related work

Many researchers are interested in using haptic feedback devices to enhance their virtual environment research because simulating touch in virtual worlds has led to increased performance in training simulators [1–3]. Haptic devices allow an operator and a computer to exchange mechanical energy. The majority of haptic devices are force feedback joysticks, although thimble and pen devices have been used in many interesting applications. By applying time-varying or position-dependent forces, the devices provide information about a virtual object's shape and surface texture. A common application of these devices is to simulate touch for learning physical skills, such as those required in surgical medicine [4–6].

The haptic interaction between a point object and a virtual wall has been investigated by a number of researchers [7–9]. Achieving stability is recognized as a primary concern because haptic devices tend to vibrate when interacting with a hard virtual surface. Several researchers have attempted to overcome this problem by applying control theory. Kazerooni and Her [10] developed a sophisticated analysis that accounts for the dynamics of the human arm and its relationship with the haptic devices. Their model requires that the haptic device measure the force exerted by the operator on the device, but many force-feedback joysticks are manufactured without a force transducer to provide this information. Colgate et al. [11] present a control theory model that requires the device to sense only position information and to apply a linear response force as the cursor intrudes into the wall. They conclude that this approach can provide walls that feel 'stiff' if the following conditions are met: (1) the position is sampled quickly and (2) the haptic device has a large amount of inherent damping. Since programmers are often not in a position to change the damping coefficient of the haptic device, they must concentrate on sampling positions quickly. Chen and Marcus [12] report "The common rule of thumb for stable, smooth, and crisp force-feedback control loops dictates that the servo rate should be at 1000 Hz or above". Chang and Colgate [4] report that their unpublished experiments show that haptic devices require an update rate of 500 Hz–1 kHz. Several other approaches to dealing with haptic interactions with solid objects, including Zilles and Salisbury's object model [13] and Adams et al. [14] virtual coupling network, also require update rates on the order of 1 kHz.

To reduce vibration associated with slower update rates, designers typically choose to have the device respond with a force proportional to the distance inside the surface (linear gain), up to a maximum attainable force. A high gain prevents the user from penetrating very far into the surface of the object, but tends to create more noticeable vibrations. A low gain does not create much vibration, but allows the user to penetrate deeply into the surface of the object, making the object feel spongy rather than stiff. The maximum obtainable force depends on the device. Zilles [13] reports that "most users tend to use less than 5 N of force" when exploring virtual environments. Many devices provide much greater forces, such as 18 N for the Phantom [15] and 6.5 N for the device used in the experiments reported here [16].

One of the first efforts in collaboration between the Colleges of Dentistry and Engineering at Iowa was a study designed to quantify the types and variety of forces exerted by dentists while they explore teeth for carious lesions. This study indicated that a simulator would need to provide forces in the range of 0.16–1.96 N, which is readily attainable with commercial force feedback devices.

2. System design

2.1. System description

The Iowa Dental Surgical Simulator currently consists of three hardware components: the computer, the monitor and a force feedback device and software. Ultimately these components will be integrated with a plastic model of a patient (See Fig. 1). The monitor displays the cross sections of two teeth — a preparatory tooth and a normal tooth with a carious region — at 640 × 480 pixel resolution, placed low and in a box in order to emulate the position of a patient's head. A 200 MHz PC computer drives the simulation. Participants interact with the computer by grasping a joystick handle or explorer handle attached to the force feedback device (an Immersion Corp. Impulse Engine 2000 [16]). The force feedback device asserts resistive forces whenever the operator attempts to move the on-screen cursor past the edge of the graphically rendered teeth.

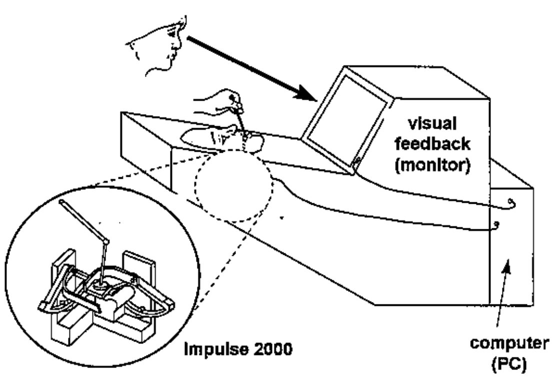

Fig. 1. The targeted Iowa Dental Surgical Simulator will integrate the current system, which consists of the monitor, force feedback device and two handles, with a physical model of a patient.

The haptic device, a two-degree of freedom joystick, consists of a 14-cm long hard plastic handle or dental explorer handle atop a metal box housing the direct-drive feedback motors. At its tip, the device can produce a maximum force of 6.5 N. Since the joystick rotates, the workspace describes a portion of the surface of a sphere with a radius of 14 cm. The optical encoders mounted on the motor shaft provide a position resolution 0.02 mm. Joystick position was represented in a 700 × 700 pixel window on the monitor screen. Two types of handles could be attached to the device, a standard joystick or a modified handle from an explorer, a dental instrument used for exploring tooth surfaces for carious lesions (see Fig. 2).

The software consisted of two threads (Fig. 3). The first thread looped 1000 times per s during which time it read the x, y position of the cursor, calculated an appropriate response force, typically directed normal to the contacted surface, and sent force commands to the force feedback device. This software communicated to the force feedback device through a digital to analog converter card supplied with the haptic device. The second thread looped approximately 30 times per s and updated the screen graphics. All the software was written in C and C++ and was derived from the demonstration code shipped with the device, which simulated rigid and pliant circles and a simple spring.

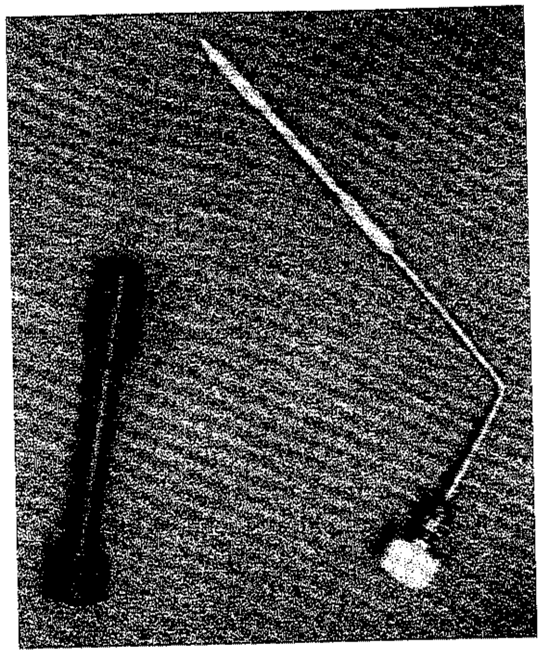

Fig. 2. The two handles that can be attached to the force feedback device: the joystick handle (left) and explorer handle (right).

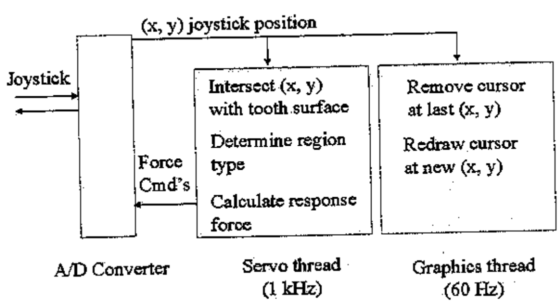

Fig. 3. Software flow diagram. The haptics and graphics threads both reside on a 200 MHz PC with the WINDOWS 95 operating system. The computer is equipped with an analog to digital converter card that communicates with the joystick.

2.2. Force model

One of the major extensions to the original software was the development of force models for different tooth regions — healthy enamel, healthy dentin, and carious dentin (see Fig. 4). These models were developed through an interview with a practicing dentist then through several informal evaluations by the same dentist over a period of 6 months. The models differ in the manner in which response forces are calculated. There are five force types used to simulate different tooth features. In the ten-pixel buffer above healthy enamel and dentin, forces range between 0 and 6.5 N in a direction normal to the tooth surface. Below the buffer region, the incursion force model applies an upward force of 6.5 N and a lateral force that varies linearly between 0 and 6.5 N depending on the horizontal distance from the initial incursion. For carious dentin, buffer and incursion models are used, but the maximum force magnitude is 1.3 N, to simulate the sponginess of carious dentin.

When the cursor enters a carious lesion in enamel, lateral departures are treated in the same manner as lateral motion inside healthy enamel, but no vertical force is applied. This essentially models a small hole below the tooth surface. When the cursor is extracted from the carious lesion a downward 'tug' force is presented, which varies linearly from the bottom of the carious lesion with a maximum value of 4 N for carious dentin and 6 N for carious enamel.

A hard physical surface provides resistive forces that are equal to the force applied. This behavior can only be approximated with the device used here because there is no sensor with which to measure the applied force. This limitation is overcome by providing increasing forces at deeper depths, which implies a tradeoff between the perceptual sponginess of the surface and the vibration caused when the device responds with a force much larger than the applied force. Incrementing

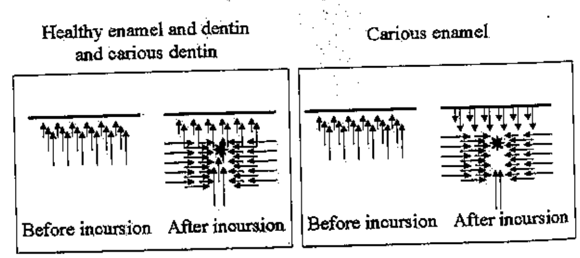

Fig. 4. Force vector fields for the various types of dental surfaces. The healthy tooth surfaces and carious dentin differ only in the magnitude of their resistive forces. When the cursor (star) intrudes into the surface, resistive forces prevent lateral motion. The carious enamel provides a small pocket below the surface with no resistive forces.

the magnitude of the applied forces at deeper cursor depths provides an opportunity to resist penetration with an appropriate response force before the user has moved deeper into the tooth, where he or she will receive a larger than appropriate response force.

2.3. Update rate

In order to respond to tooth incursions with an appropriate force, the joystick must be updated frequently with a servo algorithm that calculates the depth of intersection and sends the required force to the haptic device. Fast update rates require simple servo algorithms, particularly when other processes, such as the graphics refresh thread, run on the same computer that runs the servo functions. The graphics and the servo routines must compete for the system resources, necessitating a tradeoff between realism and complexity of the simulation with the need for a fast update rate.

The computer maintains a 1 kHz update rate because both the graphics and the servo algorithm are designed to efficiently calculate forces from a linear interpolation of the x-coordinate between points located along the tooth surface. This is followed by a calculation of the probe depth relative to the interpolated line. The graphics thread only redraws the rectangle around the last and new cursor positions with each refresh in order to avoid costly screen redraws.

A controlled evaluation experiment, which tested the effectiveness of this design with experienced dentists is described below.

3. Evaluation

3.1. Purpose

The evaluation was designed to answer the following two research and design questions:

1. Does the simulator provide realistic forces in the force feedback joystick when interacting with enamel, healthy dentin and carious dentin for expert practicing dentists?
2. What improvements are required to the design of the simulator? Is the hand position natural and comfortable? Is the tactile feedback (touch) realistic? Is the user able to concentrate on probing (feeling) for caries rather than on operating the simulator? Do the rudimentary graphics interfere with probing for caries?

A secondary purpose of the evaluation is to identify research questions that can be answered regarding the instruction and assessment of tactile dental skills.

3.2. Methodology

A review of the literature reveals formative evaluation techniques that include one-on-one and small group protocols with the intended audience [17,18]. Because the development of the surgical simulator is in its very early stages and the primary goal is to validate the haptics, this formative evaluation involved only experts [19]. The evaluation consisted of two parts — pilot tests with dentists and a group interview with all of the participants. Twelve certified dentists (volunteers) who had been practicing for 5 or more years provided information about the haptic values and design of the IDSS.

3.2.1. Practitioner Pilot Tests — gather haptic information

The Practitioner Pilot Tests protocol was designed to identify and correct design flaws in the haptics of the prototype simulator. The twelve participants were randomly divided into two experimental groups — Group A and Group B (Table 1). Group A 'explored' one tooth for caries using the joystick and then switched to the explorer to probe the second tooth. The second group explored a tooth first using the explorer and then probed the second tooth using the joystick. In order to avoid any side effect that may occur from the order in which the teeth were probed (order effect), participants within each group alternated which tooth they probed first. The research design was a 2×2 factorial design (cross-over).

Each participant spent up to 2 min with the demonstration program to completely understand

Table 1
Formative evaluation design

Group/probing	Practice	First experience; questions	Second experience; questions
Group A1 ($N = 3$)	Yes	Joystick — carious lesion	Explorer — preparation
Group A2 ($N = 3$)	Yes	Joystick — preparation	Explorer — carious lesion
Group B1 ($N = 3$)	Yes	Explorer — preparation	Joystick — carious lesion
Group B2 ($N = 3$)	Yes	Explorer — carious lesion	Joystick — preparation

the operation of the force feedback device. Then they began probing. Each participant had up to 5 min to probe the assigned tooth, followed by a series of predetermined questions.

The cross section of two teeth were presented on the screen (Fig. 5). The tooth on the right contained a carious lesion in the central groove of a mandibular molar; the tooth on the left tooth contained a preparation for a restoration. The goal of probing the right tooth was to determine the presence of caries; the goal of probing the left tooth was to detect if all of the dentinal caries has been removed, where dentainal caries are defined as residual demineralized dentin.

A researcher was present at all of the pilot test sessions and took notes regarding participant actions and asked the survey questions. In addition, a camera videotaped each session and recorded the activity on the screen, including a display of the system clock. It also recorded all comments made by the participants. The dentists were instructed to 'think out loud' during the entire session. During each session a continuous stream of force data exerted by the haptic device was recorded by the computer along with a time stamp.

Previous studies [20] indicated that the amount of force exerted by a dentist may increase when a lesion is expected. In order to confirm this, the dentist was asked to continuously state their current clinical finding (healthy enamel, health dentin, or carious dentin). These statements combined with the videotaped and recorded forces allowed the researchers to match practitioners' comments with the forces exerted during a post hoc review. Thus the researchers were able to match comments like 'This feels cheesy.' with the forces exerted at that point in time.

4. Analysis

4.1. Dentist questionnaire

After probing a tooth each practitioner answered a series of questions some of that were the same for each situation and some that were unique to the probing experience. Table 2 summarizes the questionnaire items and their responses on a scale of 1–5 with 1 being negative and 5 positive.

4.2. Common questions

The boxplot in Fig. 6 presents the practitioners' responses to each of the first eight questions. The figure indicates considerable variation in the dentist's perception that the simulation of the healthy enamel and dentin was realistic, with the mean of

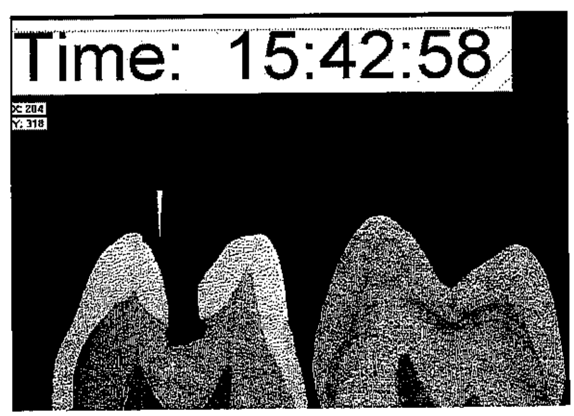

Fig. 5. Illustration of the monitor screen during the experiment. The tooth on the left shows has been prepared for reconstruction (a preparation). A small portion of the dentin at the bottom left of the preparation is carious. The tooth on the right has a carious lesion in the top, middle portion of the tooth.

Table 2
Summary of participant responses

10	Rank in order of importance, with 1 being the most important, the possible	145 *N*	Mean (1.6) Mean (1–5)	S.D. S.D.
Common questions				
1	The feel of the surface enamel and healthy dentin is realistic	24	3.0	1.5
2	I feel comfortable using this instrument (as opposed to the other instrument)	24	3.6	1.2
3	I am able to concentrate on testing for caries versus using the simulator	24	3.8	1.3
4	The two-dimensional graphics are of sufficient quality	24	4.2	0.8
5	The position of my hand when using the instrument is natural	24	2.8	1.6
Carious tooth questions				
6	The 'feel' of the enamel overlying the carious lesion is realistic	12	2.6	1.7
7	The 'feel' of the pop when I found the carious lesion is realistic	12	1.9	1.7
Preparation questions				
8	The 'feel' of the carious dentin is realistic	12	3.2	1.5
Ranking questions				
9	Rank in order of importance, with 1 being the most important, the possible improvements to this simulator as a tool for teaching tactile sensitivity			
	Graphics	24	3.2	0.6
	Force feedback device	24	2.2	1.0
	Physical model of the patient	24	3.4	0.8
	Forces delivered by the device	24	1.2	0.4
10	Rank in order of importance, with 1 being the most important, the possible improvements to the realism of the simulator		2.9	
	Graphics	24	2.5	0.9
	Force feedback device	24	2.8	1.0
	Physical model of the patient	24	1.8	1.1
	Forces delivered by the device	24		1.0

3.0 indicating that overall they were marginally satisfied with its realism. The plot also indicates that most of the practitioners were comfortable with the instrument handles and were able to concentrate searching for caries with the simulator. The results for question 4 indicate that, with the exception of one outlying point, they were quite satisfied with the graphics in the simulator. The results of question 5 indicate that although participants were generally satisfied with their hand position, there was substantial variation among the participants that ranged from highly unsatisfied to very satisfied. For three tooth specific questions, the plot indicates that the participants were undecided about the success of the modeling of the enamel overlying the carious region, but were generally satisfied with the tug or 'pop' sensation when extracting the cursor from the carie. The participants also diverged with respect to the feel of the carious dentin in the tooth with the preparation, but were, on average, satisfied with the simulation.

A general linear model ANOVA of each of the first five questions determined the effect of instrument, tooth type, order of tooth presentation, order of instrument presentation, and the order of presentation interaction. The only significant effects ($P < 0.1$) were for the order of presentation interaction in question 1 and the effect of instrument in question 5.

The significant tooth order by instrument order interaction in question 1 ($F(1,18) = 4.90$, $P = 0.04$) is shown in Fig. 7. This plot indicates that participants who began with the explorer on the caries did not think the simulation was realistic. Tukey's test with a family error rate of 5% indicates that these participants responded more negatively than those who began with the joystick on the caries did. With a family error rate of 20%, Tukey's test indicates that the participants beginning with the explorer on the caries responded more negatively than all three other groups of participants. The three other groups of participants were generally satisfied as indicated by their mean response of 3.44.

The significant instrument effect in question 5 ($F(1, 18) = 5.5$, $P = 0.03$) indicates that the handle used on the device played an important role in the

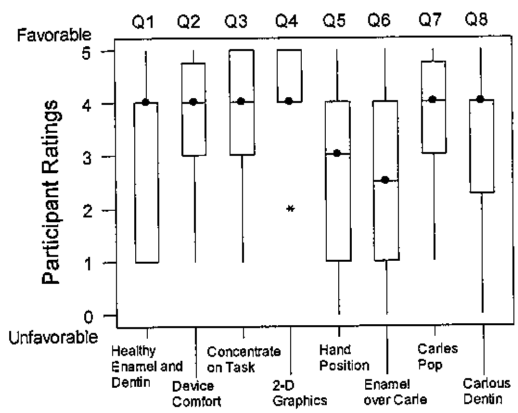

Fig. 6. Boxplot of participant responses to each of the first five questions. The first five questions each represent 24 responses, 12 on each tooth type. The last three questions represent 12 responses and apply only to one tooth. The circles on the plot represent the median response. The large time stamp facilitated correlation between the videotape and the recorded force and position files. The top and bottom of the boxes show the location of the first and third quartiles. The whiskers extend to adjacent values within 1–1/2 times the height of the box. Data beyond this range are indicated by an asterisk.

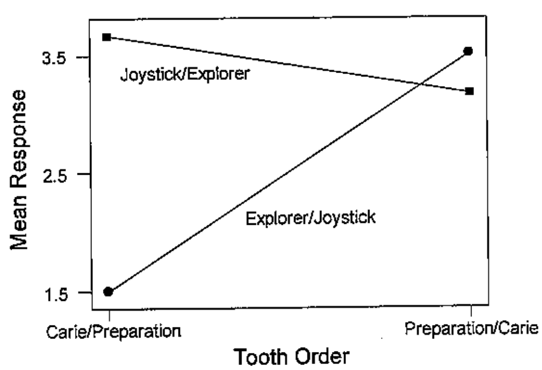

Fig. 7. The instrument order by tooth order interaction plot indicates that participants were generally satisfied with the feel of the healthy enamel and dentin unless they began with the explorer on the carious lesion in the enamel.

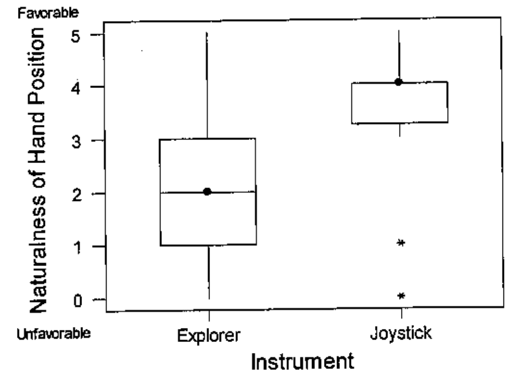

Fig. 8. A boxplot of participants' responses to the naturalness of their hand position versus the instrument type shows that the joystick afforded more natural hand positions.

naturalness of the practitioners' hand position. A boxplot of the participants' responses by the instrument type is provided in Fig. 8. A one-sided t-test ($T(21) = -2.57$, $P < 0.01$) indicates that practitioners found the hand position with the explorer handle to be less natural than the joystick handle.

Instrument, instrument order, and tooth order were not significant in the three remaining, tooth-specific questions. These effects were tested using a general linear model ANOVA.

4.3. The relative importance of improving different system components

For questions 9 and 10 the participants ranked the importance addressing improvements to the four main components of the simulator. These data were analyzed by assigning 1 point for a rank of 1, 2 points for a rank of two, and so on. Boxplots of these results are presented in Fig. 9.

An ANOVA performed on participant responses for question 9 for the effects of components, tooth, instrument, tooth order and instrument order and their second order interactions with components showed no significant effect except for the main effect of components ($F(3, 76) = 23.5$, $P < 0.001$). Tukey's with a family error rate of 5% on the four category data indicated that practitioners felt that improvements to the tactile feedback was the most important aspect of the system to improve for teaching tactile skills in dentistry. The haptic device itself was the second priority. The relative importance of the patient model and graphics was not clear, but both were ranked behind the other components.

A similar ANOVA for question 7 indicated that the only significant effects were the component ($F(3, 76) = 6.56$, $P = 0.001$) and the component by instrument order interaction ($F(3, 76) = 2.70$, $P = 0.052$). A Tukey's test with a family error rate of 5% indicated that forces delivered were more important to the realism of the simulator than either the physical patient model or the graphics. With a family error rate of 10%, however, Tukey's

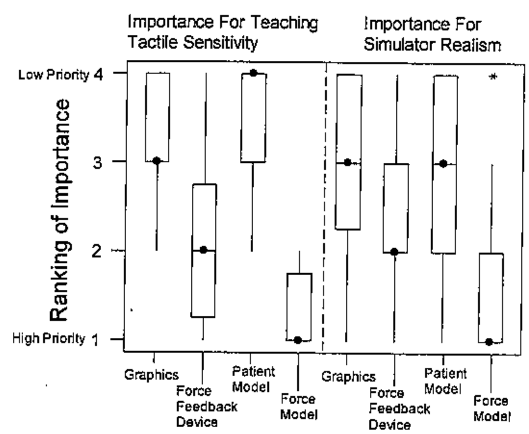

Fig. 9. Dentists' rankings of the relative importance of improving each of the four main components of the IDSS for training purposes (left) and realism (right).

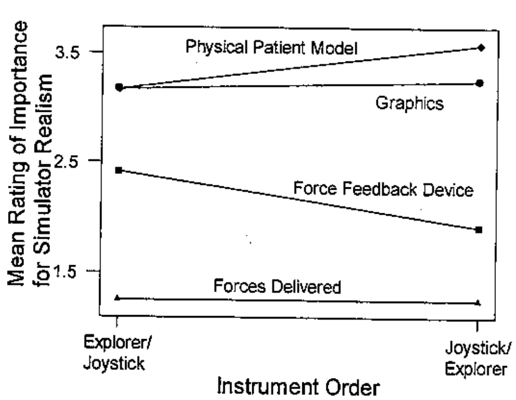

Fig. 10. Interaction plot of dentists' ranking of importance of four subsystems to the realism of the simulator versus instrument presentation order.

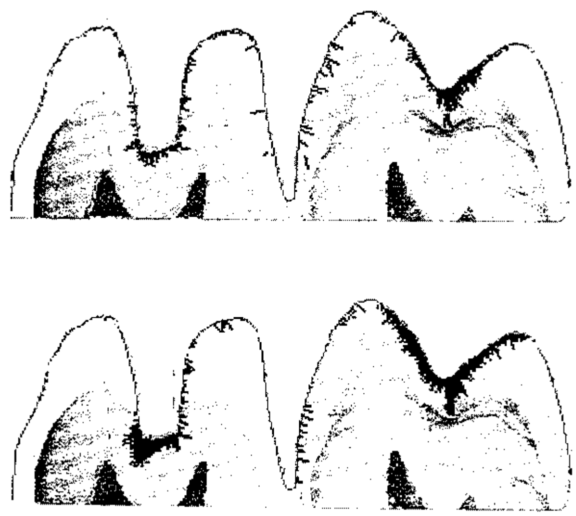

Fig. 11. Illustration of the forces applied by the device during a dentists' probing for dental caries. The black regions are vectors describing the direction of the exerted force. The length of the vectors is proportional to the force exerted. The tip of the vector indicates the location at which the force was presented.

test indicated that the participants ranked the force model above all other factors and the other factors could not be statistically resolved.

The interaction between the condition and the order of instrument presentation is illustrated in Fig. 10. This figure indicates that participants who used the joystick before the explorer tended to place more importance on improving the device than did the participants who began with the explorer.

4.4. Force data

During each trial, the joystick response forces were recorded at 6 Hz. A sample of two sets of these forces and their position in the display is presented in Fig. 11. The dark areas in the figure are vectors representing the reaction force produced by the simulator. The upper tip of these vectors shows the position of the cursor tip at the moment the force was delivered. The figures indicate several aspects of the practitioners' strategy in exploring the teeth. In both examples, the practitioners concentrated their efforts in suspicious areas indicated by the graphical display.

Participants tended to ignore other areas. The participants varied widely in the amount of force exerted. The top image is representative of those dentists who tended to use less forces when exploring for caries.

The possible causes for the probe's vibration were further explored. Forces are generated in the device through a simple control loop. Initially various gain values were explored, under the assumption that too large a gain was producing control instabilities. Eventually the problem was discovered to lie in the device resolution, a fault caused by a rounding error that reduced effective resolution by a factor of ten. The vibration was considerably reduced when the resolution was improved.

An experiment quantified the effect of spatial resolution on vibration magnitude. Keeping the gain (0.97 N m/°) and update rate (930 Hz) constant, the spatial resolution was modified from 0.13° (about 0.29 mm) to 0.013°. In each case, the position of a 200-g weight hung from the joystick was recorded. With greater spatial resolution, the output forces varied smoothly (in 141 increments over a range of 0–0.758 N m), whereas they moved in large steps (40 increments over the same range) with the low spatial resolution. The S.D. of the position of the dead weight was taken as the measure of vibration magnitude. This measure decreased from 0.12 to 0.052° with better spatial resolution. Clearly, the sensor resolution as well as servo rate and gain effect the perception of vibration.

5. Discussion and conclusions

The results of our analyses indicate that the practitioners were generally satisfied with the simulator, as indicated by the frequent median responses of 4 on a scale of 1–5. The experiments also indicate specific areas that need to be addressed. Contrary to our initial ideas, graphics was not a critical target for development, although, as we suspected, the effect of grip design and the quality of the force feedback device was quite important. A review of the videotape and the comments made during a debriefing session indicated that the vibration of the device on the tooth surface dominated the participant's experience with the simulator. Vibration seemed to affect different participants to different extents, which we believe to be the reason for the wide variation in responses regarding the quality of the forces. The explorer handgrip also seemed awkward to many participants. Those participants who began the experiment with the least favorable condition, the explorer handle on the carious lesion, seemed to have been negatively biased throughout the experiment.

The design of haptic components is dominated by the users' sensitivity to vibration. Controlling the vibration requires a delicate tradeoff between the realism of the forces and the update rate. This work demonstrates some success in developing a force model that allowed dentists to detect carious lesions in enamel and dentin, but clearly indicates that further work is required to reduce the distracting vibrations.

The vibration may be eliminated by increasing the servo rate, improving the spatial resolution, or increasing the device damping. The vibration may also be controlled by using control theory to find the optimal gain. The control theory approach is limited, however, by the variable interaction between the operator's hand and the device.

The perceived stiffness of the virtual wall is still limited by the maximum stable gain of the device. Other techniques may be used to increase the perception of stiffness. Salcudean [9] used a method of applying an additional jolting force to the device at intersection to augment the stiffness of the object. Second, visual perception may be dominant over the sense of touch. So one technique is to graphically display a greater stiffness than what is actually felt [21]. For example, if the graphical display only moves one pixel when it should move two, the brain will interpret movement of only one pixel even though the hand feels it moving more.

The issue of the handgrip design is closely related to the two degrees of freedom available with the device used here. A dental tool in free space inherently has six degrees of freedom, x, y, z and roll, pitch and yaw. The dentists expressed a strong desire for the simulator to behave in the same manner that a normal dental instrument behaves. Haptic devices capable of six degrees of freedom are more complex and expensive than the present device, which would limit the ultimate application of the simulator in practical educational settings. Furthermore, adding degrees of freedom to the device naturally leads to more complex, three-dimensional graphics, which would further tax the computer resources necessary for a fast servo loop. Due to cost considerations, it may be advantageous to pursue a less complex device and develop better mechanical mappings of the force model. An example of such a solution might be the Phantom (SensAble Technologies), which provides forces along the x, y, and z axes as well as passive degrees of freedom for roll, pitch and yaw.

This work is the first to describe the design and implementation of a force feedback dental simulator and to provide an experimental evaluation of its potential effectiveness for training tactile skills to dental students. The results indicate that the force feedback device and the force model are the most important areas for further improvement, although the participants were generally pleased with the current implementation. Further analysis of the experiment indicates that eliminating vibration when the device is in contact with hard surfaces and using a device with more degrees of freedom should be among the top priorities for future development.

This work leads to the following recommendations for designers of haptic interfaces for applications including dentistry, manufacturing, repair and surgery:

1. Elimination of device vibration is critical to success
2. Haptic servo loops are a higher priority than graphics quality
3. Theatrical props and other environmental factors to increase the visual realism of the simulator are a relatively low priority
4. A simple joystick interface may be more effective than a more realistic handle if the range of motion as the device used in practice is not preserved.
5. A graphics interface that does not correspond explicitly to the view seen by a practitioner in practice may be readily accepted.
6. A negative initial reaction to a haptic interface may negatively bias a research participant to later improvements

This work motivated and funded the research of a six-degree-of-freedom force feedback device (Phantom) in the further development of the Iowa Dental Surgical Simulator. Some other areas for future research are measuring the specific force characteristics of dental surgical procedures, measuring the training transfer between a haptic simulator and actual practice, and understanding the relationship between graphical and haptic feedback in a simulator.

References

[1] K.J. Salisbury, Phantom-based haptic interaction with virtual objects, IEEE Comput. Graphics Appl. 17 (1997) 6–10.

[2] T. Massie, A tangible goal for 3D modeling, IEEE Comput. Graphics Appl. May/June (1998) 62–65.

[3] T.H. Massie, The PHANToM haptic interface: a device for probing virtual objects, 1998 http://www.sensable.com/haptics/asme.htm.

[4] B. Chang, E.J. Colgate, Real-time impulse-based simulation of rigid body systems for haptic display, in: Proceedings of the ASME International Mechanical Engineering Congress and Exhibition, 1997, pp. 1–8.

[5] E. Chen, B. Marcus, Force feedback for surgical simulation, Proc. IEEE 86 (3) (1998) 524–530.

[6] B. O'Neill, Putting virtual reality to work: eye surgery simulator could help physicians learn and practice new techniques, Simulation December (1993) 417–418.

[7] J.E. Colgate, J.M. Brown, Factors affecting the z-width of a haptic display, in: Proceedings of the IEEE International Conference on Robotics and Automation, San Diego, CA, 1994, pp. 3205–3210.

[8] L.B. Rosenberg, B.D. Adelstein, Perceptual decomposition of virtual haptic surfaces, in: Proceedings of the IEEE Symposium on Research Frontier in Virtual Reality, San Jose, CA, 1993.

[9] S.E. Salcudean, T.D. Vlaar, On the emulation of stiff walls and static friction with a magnetically levitated input/output device, in: Proceedings of the International Mechanical Engineering Exposition and Congress, Chicago, IL, 1994, pp. 303–310.

[10] H. Kazerooni, M. Her, The dynamics and control of a haptic interface device, Trans. Robotics Automat. 10 (4) (1994) 453–463.

[11] J.E. Colgate, M.C. Stanley, J.M. Brown, Issues in the haptic display of tool use, Trans. IROS 1995.

[12] E. Chen, B. Marcus, Force feedback for surgical simulation, Proc. IEEE 86 (3) (1998) 524–530.

[13] C.B. Zilles, J.K. Salisbury, A constraint-based god-object method for haptic display, in: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Pittsburgh PA, 1995, pp. 146–151.
[14] R. Adams, M.R. Moreyra, B. Hannaford, Stability and performance of haptic displays: theory and experiments, in: Proceedings of the International Mechanical Engineering Congress and Exhibition, ASME, Anaheim, CA, 1998.
[15] J.E. Colgate, M.C. Stanley, J.M. Brown, Issues in the haptic display of tool use, in: IROS '95, 1995.
[16] Immersion Corp, http://www.immerse.com.
[17] W. Dick, L. Cary, The Systematic Design of Instruction, Scott Foresman, Glenville, IL, 1988.
[18] M. Medley, C. Weston, A comparison of student feedback obtained from three methods of formative evalution of instructional materials, Instructional Sci. 17 (3) (1988) 3–27.
[19] A. Saroyan, Differences in expert practice: a case from formative evaluation, Instructional Sci. 21 (1993) 451–471.
[20] N. Gomez, Typical forces exerted on a tooth during caries detection, The University of Iowa, 1997 Masters Thesis.
[21] M.A. Srinivasan, C. Basdogan, Haptics in virtual environments: taxonomy, research status, and challenges, Comput. Graphics 21 (1997) 393–404.