Performance of Dental Students Versus Prosthodontics Residents on a 3D Immersive Haptic Simulator

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Abstract: This study evaluated the performance of dental students versus prosthodontics residents on a simulated caries removal exercise using a newly designed, 3D immersive haptic simulator. The intent of this study was to provide an initial assessment of the simulator's construct validity, which in the context of this experiment was defined as its ability to detect a statistically significant performance difference between novice dental students (n=12) and experienced prosthodontics residents (n=14). Both groups received equivalent calibration training on the simulator and repeated the same caries removal exercise three times. Novice and experienced subjects' average performance differed significantly on the caries removal exercise with respect to the percentage of carious lesion removed and volume of surrounding sound tooth structure removed ($p<0.05$). Experienced subjects removed a greater portion of the carious lesion, but also a greater volume of the surrounding tooth structure. Efficiency, defined as percentage of carious lesion removed over drilling time, improved significantly over the course of the experiment for both novice and experienced subjects ($p<0.001$). Within the limitations of this study, experienced subjects removed a greater portion of carious lesion on a 3D immersive haptic simulator. These results are a first step in establishing the validity of this device.

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In dentistry, preclinical operative training involves the development of hand skills and the mastery of various procedures that will soon be performed on live patients. The controlled preclinical environment enables students to practice at their own pace and become proficient before entering the clinic, where patient management issues and fear of making errors might complicate the mechanical execution of dental procedures. Traditionally, this process is time- and resource-intensive, requiring extensive materials, faculty oversight, and specialized laboratory space. Therefore, computer virtual reality-based simulation systems have become an appealing alternative for dental schools attempting to make the preclinical learning experience more efficient, lower costs, and address faculty shortages.[1]

Simulators have the potential to assist faculty members by identifying students who might require extra assistance over the course of their preclinical training.[2] Computer-assisted models enable students to practice independently by providing automated feedback. Jasinevicius et al. demonstrated the value of feedback provided by these simulators: during preclinical simulation training, students who received computer-generated feedback required only 20 percent as much face-to-face faculty instruction time, but scored as well as their peers on preclinical operative dentistry examinations.[3] On initial preclinical evaluations, students exposed to computerized simulation exercises at the outset of their preclinical training outperformed their classmates not exposed to the exercises.[4]

Haptic simulators originally developed for flight simulation training have recently been adapted to teach health pre-professional students how to perform various clinical procedures. The force feedback transmitted to the hand via a haptic simulator mimics the tactile sensations that would be experienced during an actual patient procedure. 3D visualization may augment the haptic simulation experience by capitalizing on the synergy of sight and touch.[5] Haptic technology is particularly exciting for dentistry because the preclinical curriculum is devoted largely to the development of motor and tactile abilities.[6]

There are unique advantages to haptic simulators' largely software-based approach. For example, virtual experiences can be highly customized to each user's skill level and the type of procedure that he or she wishes to practice.[7] No disposable resources are required,[5,8] and these simulators create a low-stress environment in which students can repeat procedures multiple times.[9] Surveys indicate that dental students and faculty members who have practiced on a haptic simulator see its potential as an educational tool.[5,7,10]

Our objective in this study was to test the sensitivity of a newly designed, 3D immersive haptic simulator and to determine whether it has the ability to detect statistically significant differences between dental students and prosthodontics residents at performing a simulated caries removal exercise. As a substantial experience gap separated these two groups, demonstration of the simulator's ability to distinguish between them was a fundamental first step in establishing its validity.

Materials and Methods

The protocol for this study was approved by the Harvard University Faculty of Medicine Committee on Human Studies (IRB protocol # M22416-101). This was a pilot study; therefore, no power calculations for study size were needed.

The novice group consisted of twelve volunteers from the first-year Doctor of Dental Medicine (D.M.D.) class at the Harvard School of Dental Medicine. These students had received no formal preclinical training at the time of the experiment. The experienced group consisted of fifteen volunteers from the Prosthodontics Residency Program at the Harvard School of Dental Medicine. These residents have previously obtained a D.D.S. or D.M.D. degree and have varying years of clinical dentistry experience, ranging from zero to multiple years of practice prior to entry.

The simulator used in this investigation was VirTeaSy (Didhaptic, Laval, Pays De La Loire, France). After being presented with a brief verbal overview of the experiment, the subjects were shown a five-minute video that demonstrated how to use the various hardware components of the simulator (Figure 1). The subjects first completed two tutorial exercises in order to familiarize themselves with the simulator. Time was unlimited, and performance was not evaluated during these exercises. A short break was given after each exercise.

In the first of these exercises, the subject was asked to drill a hole in three blocks, each with a different density (Figure 2). The subject was made aware that the labels "C," "D," and "E" on the blocks were meant to correspond with the density of caries, dentin, and enamel, respectively. This exercise was repeated a total of eight times at high and low speeds for each of four bur options: round, pear-shaped, flat end straight fissure, and flat end tapered fissure (Figure 3). The purpose of this exercise was to introduce

Figure 1. The VirTeaSy simulator used for this experiment

the subjects to the various tools available for use in the program and also to the different densities of the tooth surfaces that they might encounter during the caries removal exercise.

The second of these exercises involved the removal of a low-density cross from a high-density block, with special attention to the contour, smoothness, and depth of the cavity excavated from the block (Figure 4). The subject was allowed to use any bur that he or she liked to perform the exercise. This exercise was designed to familiarize the subject with how to perform precision work on the haptic simulator, how to select and transition between burs, and how to manipulate the orientation of the target in virtual reality. The subject repeated this exercise two times, and a third repeat was permitted upon request.

Immediately after completion of the two tutorials, the subjects were asked to complete a caries removal exercise, which consisted of the removal of occlusal pit and fissure caries from a right lower first molar (Figure 5). The caries was indicated with bright green color and could also be distinguished from the dentin and enamel by density. During this exercise, the density of caries, dentin, and enamel was consistent with that presented during the first tutorial exercise. The subjects were reminded that data collection would take place during this portion of the session and were encouraged to perform the exercise to the best of their abilities.

Prior to beginning the exercise, the subjects were informed of the parameters to be evaluated. These parameters were the percentage of carious lesion removed, the cubic millimeters of sound tooth

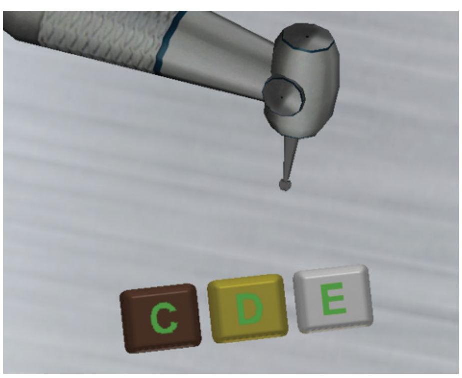

Figure 2. Tutorial 1: drilling holes in blocks with different densities corresponding to caries, dentin, and enamel

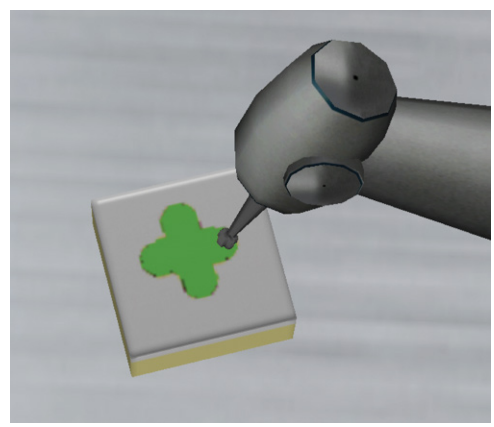

Figure 4. Tutorial 2: removing a low-density cross from a high-density block

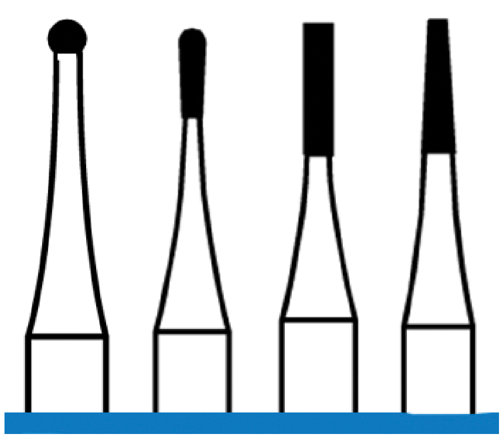

Figure 3. Bur options for the virtual exercise

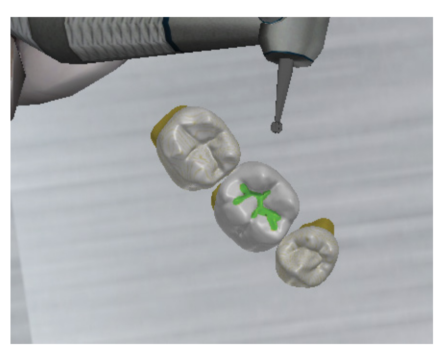

Figure 5. Caries removal exercise for evaluation

structure removed, and the total time spent drilling. Throughout the caries removal exercise, each subject's bur selection was monitored.

The stated objective of this exercise was to remove the maximum amount of caries with minimum damage to the surrounding tooth structure, dentin, and enamel. The subjects were allowed to select any bur for the exercise and were not instructed to utilize any particular caries removal technique. An unlimited quantity of time was given to perform the exercise, and the subjects were told to inform the investigator when they felt that they had completed the task. The identical caries removal exercise was repeated a total of three times. After each trial, the subjects were informed of their performance on the task that they had just completed. A short break was given between each exercise.

Upon completion of the caries removal exercises, the subjects were asked to fill out a questionnaire about their experience with the simulator. The survey consisted of statements about the subjects' comfort using the simulator, their perception of its value, and their desire to use it in the future. Members of the experienced group were asked to respond to an additional question about how faithfully the simulator reproduced their experiences with live patients in the clinic. For each statement, the subjects were asked to record their response along a visual analogue scale ranging from 0 to 100, in which 0=strongly disagree and 100=strongly agree. The position along the scale corresponded to percent agreement with the given statement.

Statistical analysis was done on SPSS (Ver. 20, IBM Corp., Armonk, NY, USA). Specifically, data were analyzed using 2 (novice and experienced groups) by 3 (simulator trials) MIXED ANOVAs, with dependent variables precision, volume, and efficiency. Precision was defined as the percent of carious lesion removed, volume as the volume of sound tooth structure removed in cubic millimeters, and efficiency as the precision divided by drilling time. Significance was considered to be a p-value of less than 0.05.

Results

Twelve novice and fifteen experienced subjects participated in this protocol. One subject from the experienced group was unable to complete all three iterations of the caries removal exercise due to time constraints and was excluded from the analysis. Execution of the entire protocol did not exceed ninety minutes; in general, no more than twenty to thirty minutes were spent on the introduction and tutorial exercises.

The primary outcome examined was the percentage of carious lesion removed or "precision" because a main objective of restorative dentistry is to completely remove caries in advance of restoration. Although some portion of the surrounding sound tooth structure will inevitably be removed during caries excavation, it is important to preserve the integrity of the tooth. Therefore, a secondary outcome was the volume of sound tooth structure removed in cubic millimeters or "volume." Another outcome considered was the amount of time that each subject applied force to the foot pedal or the "drilling time." To address the tradeoff between precision and speed, the percentage of accurate caries removal per unit time or "efficiency" was calculated as precision divided by drilling time. A summary of the outcomes is shown in Table 1.

The results of the 2x3 MIXED ANOVA with precision as a dependent variable revealed a significant effect of expertise. There was a statistically significant difference between novice and experienced precision ($F(1,24)=7.178$, $p<0.05$), so that experienced subjects removed a significantly greater portion of the carious lesion across the three trials (Figure 6, panel a). The effect of trials was not significant ($F(1,24)=2.087$, $p=0.162$), so that the precision did not change significantly from trial to trial. There was no significant interaction between trial and experience with respect to precision ($F(1,24)=0.483$, $p=0.494$).

The results of the 2x3 MIXED ANOVA with volume as a dependent variable also revealed a significant effect of expertise. There was a statistically significant difference between novice and experienced volume ($F(1,24)=5.459$, $p<0.05$), so that experienced subjects removed a significantly greater amount of the surrounding sound tooth structure across the three trials (Figure 6, panel b). The effect of trials was not significant ($F<1$), so that the volume did not change significantly from trial to trial. There was no significant interaction between trial and experience with respect to volume ($F<1$).

The results of the 2x3 MIXED ANOVA with drilling time as a dependent variable showed no significant differences between novice and experienced participants' drilling times ($F<1$) (Figure 6, panel c). There was a significant change in drilling time across the three trials ($F(1,24)=13.802$, $p<0.01$). Follow-

Table 1. Novice and experienced participants' average performance on caries removal exercise

	Overall		Trial 1		Trial 2		Trial 3	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Precision (% of carious lesion removed)								
Novice	80.1%	11.9	77.9%	12.3	80.4%	13.0	82.1%	14.6
Experienced	91.1%	8.9	90.7%	10.1	90.4%	12.0	92.2%	8.8
Volume (sound tooth structure removed in mm^3)								
Novice	17.4	9.3	17.0	13.0	17.1	9.8	18.0	12.5
Experienced	31.1	18.4	31.2	17.0	30.4	20.5	31.7	22.4
Drilling time (seconds)								
Novice	224.3	73.9	283.7	129.6	220.8	78.0	168.6	63.5
Experienced	217.2	97.8	242.3	110.4	220.1	120.3	189.3	97.0
Efficiency (precision/drilling time)								
Novice	0.43	0.15	0.33	0.18	0.40	0.11	0.56	0.26
Experienced	0.54	0.29	0.47	0.26	0.57	0.41	0.59	0.24

up, paired-samples t-tests (two-sided) revealed a significant decrease in drilling time from trial 1 to 2 ($t=2.220$, $p<0.05$), from trial 1 to 3 ($t=3.558$, $p<0.01$), and from trial 2 to 3 ($t=3.129$, $p<0.01$). However, there was no significant interaction between the change in drilling time and experience level ($F(1,24)=1.883$, $p=0.183$), indicating that novice and experienced drilling times decreased in the same way from one trial to another.

The results of the 2x3 MIXED ANOVA with efficiency as a dependent variable showed no significant differences between novice and experienced participants' efficiency ($F(1,24)=1.463$, $p=0.238$) (Figure 6, panel d). There was a significant change in efficiency across the three trials ($F(1,24)=17.660$, $p<0.001$). Follow-up, paired-samples t-tests (two-sided) revealed a significant increase in efficiency from trial 1 to 2 ($t=-2.671$, $p<0.05$) and from trial 1 to 3 ($t=-4.063$, $p<0.001$), but not from trial 2 to 3 ($t=-1.528$, $p=0.139$). However, there was no significant interaction between the change in efficiency and experience level ($F(1,24)=1.654$, $p=0.211$), indicating that novice and experienced participants' efficiency increased in the same way from one trial to another.

The pear-shaped bur was the most frequently selected by both novice and experienced subjects. Compared to the novice subjects, experienced subjects selected the flat end straight fissure more often. In general, the novice subjects had a more positive response to the simulator and were more enthusiastic about training on it in the future than the experienced subjects (Table 2). The subjects agreed that the instructions to use the simulator were clear. They could feel the difference between the various bur options and also the various tooth densities on which they were drilling.

Discussion

The novice and experienced subjects in this study each completed the same caries removal exercise on the 3D immersive haptic simulator. Measures of performance differed significantly between the two groups, suggesting that this simulator does have sufficient sensitivity to discern between users of different skill levels. This study therefore supports the construct validity of this new simulator.

Overall, the experienced subjects drilled more than the novice subjects, removing a larger portion of the carious lesion and a greater volume of the surrounding sound tooth structure. Although not assessed, differences between the two groups might be attributable to factors such as treatment approach, including the simulator's sensitivity to particular drilling patterns, and user confidence. For example, prosthodontics residents might have been willing to sacrifice tooth structure in order to remover a greater portion of decay, as it is especially important to completely remove caries before placing a restoration.

Over the course of the caries removal exercise, the novice subjects utilized low-speed burs more often than did the experienced subjects. This could partially explain their more conservative drilling patterns. It is interesting to note that the subjects tended to use fewer burs as the trials progressed.

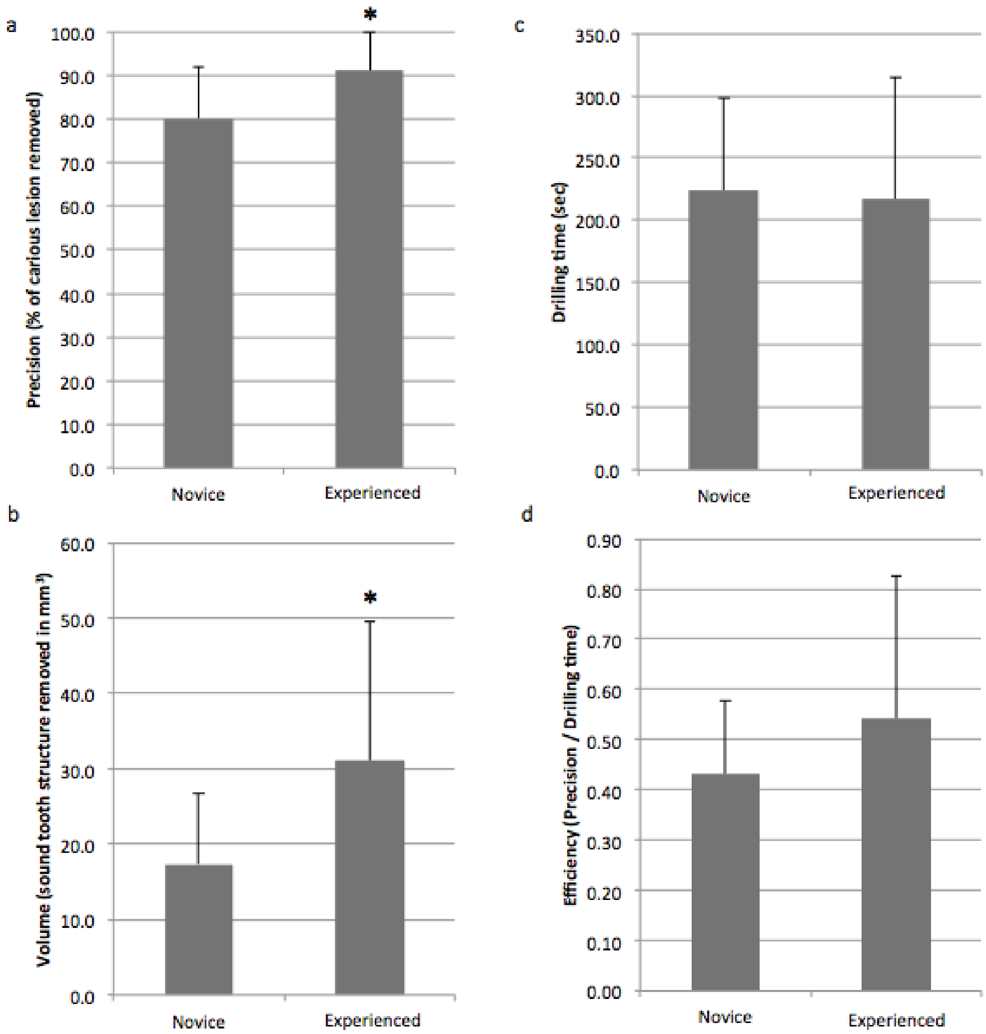

Figure 6. Comparison of novice (n=14) and experienced (n=7) participants' average performance on caries removal exercises ($p<0.05$)

This might indicate that students learn which tools are best to accomplish the caries removal exercise as they practice.

Bur selection was limited by the fact that only eight options were available during the experiment. Therefore, the subjects' selections might differ from those made in the classic approach to occlusal caries removal. For example, multiple subjects initially selected the round bur, but adjusted their choice upon realizing the drilling tip's large size relative to the carious lesion. Another limitation was lack of burs in smaller sizes due to software constraints.

As the trials progressed, the subjects performed the caries removal exercise with the same precision at significantly faster speeds. This was reflected by a significant increase in efficiency, particularly after the first trial, and suggests that learning did take place over the course of the experiment. However, both novice and experienced subjects improved in the same way, and training on the simulator did not decrease the differences between novice and experienced performance. Although both groups improved, differences between their performance did not diminish. One possible explanation is that members of both

Table 2. Responses to post-exercise survey, by percent agreement along visual analog scale

	Novice (n=12)		Experienced (n=14)	
Statement	Mean	St. Dev.	Mean	St. Dev.
I felt comfortable physically and was in a natural position while using the haptic simulator.	34%	22	38%	32
The preliminary tutorial exercises fully prepared me to perform the caries removal exercise.	48%	28	59%	29
I did not experience any physical side effects (i.e., dizziness, nausea, muscle cramping) from using the haptic simulator.	33%	36	47%	34
The haptic simulator became progressively easier to use with each exercise.	68%	19	54%	19
I would feel motivated to spend more time practicing on the haptic simulator and performing exercises such as the caries removal exercise.	52%	28	29%	23
I could feel a difference between the various burs available for use during the haptic exercises.	63%	25	62%	29
The video instruction provided about how to use the hardware components of the haptic simulator was clear.	90%	8	82%	21
The haptic simulator would be a useful adjunct to current preclinical training provided in the regular class lectures and laboratory demonstrations.	60%	19	30%	23
The virtual environment created by the haptic simulator is realistic.	36%	30	31%	32
I could feel a difference between the various tooth surfaces (enamel, dentin, carious) presented during the haptic exercises.	81%	17	65%	28
The caries removal exercise closely approximated caries removal in the clinical setting.	–	–	19%	19

groups became more adept at using the simulator over the course of the caries removal exercise.

Our findings are in concordance with those reported by others who have investigated the construct validity of haptic simulation devices for dental training purposes. Suebnukarn et al. demonstrated the ability of a haptic simulator to distinguish between novice and expert execution of crown preparation tasks.[6] The fact that those with distinct levels of clinical training consistently performed differently on dental-specific haptic simulation exercises confirms the validity of this technology. The expanded capabilities of the simulator assessed in this study, including a 3D immersive environment, have the potential to further enhance the virtual experience. As technology evolves, so will its capacity to contribute to education, particularly with respect to procedural training.

There was a fairly wide range in the survey responses. The subjects acknowledged that the simulator became progressively easier to use, suggesting that they were aware that learning took place as they practiced. The subjects did not feel that the exercise was realistic or that it closely approximated their clinical experiences. However, the purpose of the simulator is not to replace reality, but rather to provide an alternative to the odontotype traditionally used in preclinical training. Future assessment should include questions comparing subjects' response to the 3D immersive haptic simulator versus classical preclinical training methods.

Conclusions

Within the limitations of this pilot study, experienced subjects removed a significantly greater portion of carious lesion, as well as surrounding tooth structure, on a 3D immersive haptic simulator than did novice subjects. This finding suggests that the simulator has the ability to distinguish performance between users with different levels of preclinical and clinical training and, therefore, is valid for future experimentation.

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