The Use of Haptics to Predict Preclinic Operative Dentistry Performance and Perceptual Ability

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Abstract: The aim of this study was to test whether performance on a range of manual dexterity haptic simulator exercises was associated with preclinical operative dentistry examination and Perceptual Ability Test (PAT) scores. Thirty-nine first-year dental students were tested with three haptic exercises—straight line, circle, and mirror line—each performed twice. Haptic exercise outcomes for accuracy, time, and success rate were measured using commercially available computer software. Spearman correlation coefficients and Student's t-test were used to assess the results. PAT and exam scores were not significantly correlated. Significant correlations were observed between exam scores and both time and accuracy scores for the circle and mirror exams. These results suggest that haptic devices have a potential role in predicting performance in preclinical dental education. Further studies are warranted to develop and validate diagnostic testing strategies for dental students and to evaluate implementation of haptics in the dental teaching environment.

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Manual dexterity is an important aspect of clinical dentistry, but despite many attempts to date, there are no standardized means of determining the manual dexterity potential of dental school candidates.[1-5] While Dental Admission Test (DAT) scores have been consistently shown to be valid predictors of academic performance in years one and two of dental school,[6] they are less useful as predictors of preclinical performance.[7] Of the individual DAT scores, the Perceptual Ability Test (PAT) score helps to explain the variance attributable to preclinical and clinical success[8] compared with the didactic or cognitive component alone.[6] Overall, however, the PAT score explains only 10 to 15 percent of the variance of the preclinical and clinical grades.[6] Hence, while traditional measures for dental school admission appear to adequately predict students' academic success, predictors of their success in the clinic and preclinic are less clear. An accurate and validated manual dexterity test would therefore be of potentially great importance to dental educators.

Computer-assisted simulation training has been found to have some utility in the preclinical operative dentistry curriculum[9-12] and may have potential as a means of assessment as well. Imber et al.[13] used a computerized dental simulator (CDS) pretest on handpiece-naïve students prior to their enrollment in a preclinical operative dentistry course. That study found that failure on the CDS pretest could predict below the median preclinical operative dentistry performance with 77 percent sensitivity and 77 percent specificity. Gray et al.[14] also tested handpiece-naïve students and found a significant correlation between students' CDS pretest scores and subsequent preclinical operative practical examination scores. In our own previous study, we observed that students who had difficulties on the CDS also had difficulties later in the course.[11] The consistency of these findings led to the hypothesis that the CDS pretest of handpiece-naïve students could predict preclinical performance and serve as a screening tool to identify students most likely to have difficulty in the course. Subsequently, we demonstrated in a study of a handpiece-naïve first-year dental student cohort that students' success on a CDS pretest predicted early practical examination performance in an operative dentistry course with 72 percent sensitivity and 92 percent specificity.[15]

CDS devices thus appear to hold promise for teaching and testing in preclinical operative dentistry. There are limitations, however, to the use of computer-assisted dental simulators—one being the cost of CDS installations and maintenance, and the other being the time required for dedicated personnel to administer the training and testing. Characteristics of an ideal computer-assisted dental trainer therefore would include low cost, low maintenance, portability, and user-friendly computer interface.

Recently, haptic technologies have been developed that offer some of these characteristics and may be suitable alternatives to CDS installations for some applications. Haptics relies on computer-assisted force feedback to produce a tactile sensation for the user. Several haptic devices have been designed to simulate the feel of a dental handpiece so that the operator may experience some of the visual and tactile simulation of an operative dentistry procedure. Hence, desktop haptic devices combined with simulation software may offer the operator a safe and inexpensive method for practicing manual dexterity skills that have some parallels with preclinical training.

To date, however, there have been no studies of haptics as predictors in preclinical or other relevant dental school admissions assessments. If haptic devices prove to be useful for teaching and/or testing of students' manual dexterity abilities, it may have important ramifications for educators. Such devices may offer the student a means of practice and feedback independent of faculty input in order to improve manual skills and possibly ease the transition into the clinical environment. Also, validated pretests may make it possible to predict subsequent preclinical and clinical student performance and identify students most in need of additional assistance.

For this study, we hypothesized that performance on a haptic test or range of tests is associated with preclinical performance and PAT scores. Our aim was to test whether performance on manual dexterity haptic simulator exercises was associated with traditional preclinical operative examination test scores or PAT scores of the DAT. The overall goal of this research is to examine alternative approaches to the assessment and teaching of students' perceptual and motor skills.

Materials and Methods

All thirty-nine first-year dental students enrolled in the Operative Dentistry I preclinical course at the Stony Brook School of Dental Medicine participated in this study. Although the protocol was deemed exempt from review by the Committees on Research Involving Human Subjects at Stony Brook University, all participants were informed of the nature of the study, and all students gave written informed consent and were given the opportunity to opt out without academic consequence.

The Operative Dentistry I course is eight months long, starting in October and ending in June of the first academic year. The course consists of 110 hours of in-class laboratory-based instruction and forty-five hours of lectures. The instructor-student ratio is, on average, 1:8. During the course, students' practical skills are tested with three practical preclinical exams that are administered in the early, middle, and end months of the course. In the year of our study, the first exam (Exam 1) took place two months after the course began and tested students' performance on a Class II mesio-occlusal cavity preparation on the first mandibular left molar of a mounted typodont (Columbia Dentoform, Long Island City, NY, USA). The students were required to observe simulated clinical conditions pertaining to infection control, i.e., mask, gloves, and rubber dam in place. Students were unaware of the tooth assignment until the day of the exam. Four calibrated course faculty members, who were masked to student identity or study participation, evaluated the students' Exam 1 typodont teeth using predetermined objective criteria. Evaluation criteria included cavity preparation external and internal outline, depth, definition, and retention. Each tooth preparation in Exam 1 was evaluated by at least two instructors independently using a scale of 60 to 100. The scores of each of the two raters on any given examination were assessed for reliability, and all resulting correlation coefficients were between .69 and .90. Students' final scores on each examination consisted of the average of two evaluators' scoring of the tooth preparation.

Students' PAT scores were obtained from admissions records. Possible PAT scores are from 1 to 30, where 30 is the highest achievable. Students admitted to dental school usually have scores ranging from 16 to 25.

Assessment System

The Individual Dental Education Assistant simulator (IDEA, Inc., Las Vegas, NV, USA) was used in this study. The Individual Dental Education Assistant is a commercially available computer-assisted simulator that uses haptic technology. It has been designed as an educator/simulator/trainer that uses a contemporary gaming approach in conjunction with high-precision haptics interfaces. The system consists of a handheld stylus device (SensAble Technologies, Inc., Woburn, MA, USA) that simulates a dental handpiece by providing force feedback. The student operator holds the device while observing the simulation on the computer display. Manual dexterity in this module is defined as one's ability to perform activities in a 3D environment that require hand-eye coordination. The haptic software and training system use an interactive approach to teach, train, and test the user on the performance of various tasks, helping the user develop manual dexterity during the process. The first objective for this system is to allow users to familiarize themselves with the simulator hardware and software. The second objective is to test the user's hand-eye coordination skills.

The virtual reality test environment is a surface featuring different paths coated in material that needs to be removed by the user. The paths may be of different shapes (e.g., straight line or circle), and the shapes can be shown in a virtual mirror. In the mirrored test, the surface is flipped on the X-axis and reflected in the mirror located at the lower side of the screen. In the mirrored situation, the user moves the stylus in the opposite direction of that desired.

The carving, or removal of structure, is done using a simulated dental handpiece controlled by a haptic input device. To attain high scores, the student is required to consider two main parameters: pace and precision. At the beginning of the test, the student receives a quantity of accuracy in his or her accuracy bar and a limited amount of time to finish the level. The parameters "time" and "percentage of removed area" required for the student to succeed can be pre-set by the instructor. During the carving activity, the accuracy bar is reduced whenever the carving deviates from the predefined path. The accuracy bar decreases more rapidly as the deviation distance and carving depth from the predefined path increase. If the accuracy bar is depleted, the test ends with failure. To motivate the student to carve as quickly as possible, a score bonus proportional to the time remaining is added to the final score. If the student is carving too deeply, touching the nonremovable material, or applying excessive force on the handpiece, a warning sound will prompt the user to adjust appropriately before the level ends with failure. Completion is limited to the time allotted for the test, but the exercise may be completed with time remaining. More time remaining following successful completion results in a higher score.

Evaluation of Data

The computer software generates data for the following: carving distance from the path, time elapsed since beginning the test, carving depth, removed area percentage, haptic force (pressure used on the handpiece), and handpiece position. The data are then compiled into a report with the following elements: 1) time remaining at the end of the test (TL); 2) time remaining at the end of the test if the exercise is successfully completed (TLC); 3) accuracy remaining at the end of the test (AL); and 4) accuracy remaining at the end of the test if the exercise is successfully completed (ALC). Additionally, a composite score is compiled consisting of a total score of all three exercises: time left completed total (TLCT), accuracy left completed total (ALCT), and time plus accuracy completed total (TACT).

For our study, in the week following Exam 1, all participants were tested using the IDEA simulator's manual dexterity module. Each student received a demonstration of three simulated carving exercises (straight line, circle, and mirror line) and instructions on how to use the haptic device. Each exercise level was preprogrammed by the manufacturer with the following parameters: 1) the straight line exercise was preset for 120 seconds and 90 percent completion; 2) the circle exercise was preset for 120 seconds and 90 percent completion; and 3) the mirror line exercise was preset for 180 seconds and 30 percent completion. The entire haptic session was timed to twelve minutes for each student, and each exercise was performed twice within that time. Previously defined and programmed quantitative scores (time remaining, time remaining if completed, accuracy remaining, and accuracy remaining if completed) for each exercise were compiled and exported for data analysis.

Statistical Analysis

The independent variables were success or failure on each of the haptic exercises and lowest quartile PAT score defined categorically. Continuous predictor variables were time left (TL), time left if successfully completed (TLC), accuracy left (AL), and accuracy left if successfully completed (ALC) for each haptic exercise. Additional continuous variables were three composite variables (time left total, accuracy left total, and time plus accuracy total), which were measures of success across all three exercises. The Exam 1 and PAT scores were defined a priori as dependent variables for this analysis.

We tested the hypothesis that haptic test outcomes were predictive of Exam 1 performance or PAT score. Tests for normality (Shapiro-Francia test for normal data) were used to determine distribution of data. The Spearman correlation or simple linear regression test was used to determine the relationships between the individual haptic test scores and the two primary outcome variables (Exam 1 score and PAT score). To explore the predictive value of the haptic tests on Exam 1 scores, we created multiple regression models adding independent variables in a forward selection manner, maintaining in the model those variables with p-values of less than 0.10.

Exam 1 and PAT score differences between groups of students who were successful and unsuccessful at the haptic tests were calculated using the two-sided unpaired t-test for normally distributed variables or the Mann-Whitney U test when normal distribution assumptions were not met. The data were analyzed using commercially available statistical software (STATA SE Ver. 8, StataCorp., LLC, College Station, TX, USA).

Results

The mean Exam 1 score for the students was 78.1 (SD 9.6); scores ranged from 55 to 98. The mean PAT score for this class was 19.2 (SD 2.0); scores ranged from 15 to 23. The PAT and Exam 1 scores were normally distributed (Figure 1), while the individual haptic exercise scores did not follow a normal distribution. No correlation was found between PAT and Exam 1 scores (Figure 2).

We evaluated those in the class who scored lowest on the PAT (below 18), which corresponded to the bottom quartile. This group scored significantly lower on Exam 1 (79.7±8.4 vs. 70.7±12.1) (p=0.02). There was a trend that those who scored below the class median (19) on the PAT also had lower Exam 1 scores (80.5±8.0 vs. 75.4±10.6; p=0.09).

On the line exercise (Figure 3, Table 1), thirty-four of thirty-nine students were successful on the first attempt, and thirty-six of thirty-nine were successful on the second attempt. Mean Exam 1 and PAT scores of the students who succeeded vs. those who failed in the first attempt did not differ significantly (Table 2). While those students who were successful at the second attempt did not differ in their Exam 1 scores from those students who had failed, the PAT scores of the two groups did differ as predicted. No statistically significant correlations were observed between the line exercise time and accuracy scores and Exam 1 or PAT scores (Table 1).

For the circle exercise (Figure 4, Table 1), nine of thirty-nine students were successful on the first attempt, and fifteen of thirty-nine were successful on the second attempt. Mean Exam 1 scores were higher (Table 2) for those who were successful at the first and second attempts compared with those who failed, but were not statistically significant. Mean PAT scores were higher for those who were successful at both attempts compared with those who failed, and reached statistical significance on the second attempt. Statistically significant correlations were observed between five of the eight measures of timing and accuracy of the circle exercise and Exam 1 scores, while two of the eight measures were significantly correlated with the PAT scores (Table 2). No single haptic test result was significantly correlated with both Exam 1 and PAT scores.

In the mirror exercise (Figure 5, Table 1), twenty-one of thirty-nine students were successful on the first attempt, and twenty-seven of thirty-nine were on the second attempt. Mean Exam 1 scores (Table 2) were significantly higher among those who were successful on their first but not second attempt. Those students who succeeded did not have higher PAT scores than those students who failed on both attempts. We observed trends for correlation or significant correlation between five of eight measures of time and accuracy and Exam 1 but not PAT scores for this exercise, including a highly significant correlation between the measure of time left for completion of this exercise and Exam 1 scores.

In a univariate analysis, the lowest quartile PAT score was significantly associated with the Exam 1 score ($p=0.02$, $r^2=0.13$); the other significant predictor was mirror exercise success ($p=0.01$, $r^2=0.16$). In a multivariate analysis, the addition of the mirror exercise success to lowest quartile PAT score as independent variables resulted in an increase in the predictive value of the Exam 1 score ($p=0.008$, $r^2=0.24$). (See Table 3.) The remaining haptic tests were not significant when added to the model.

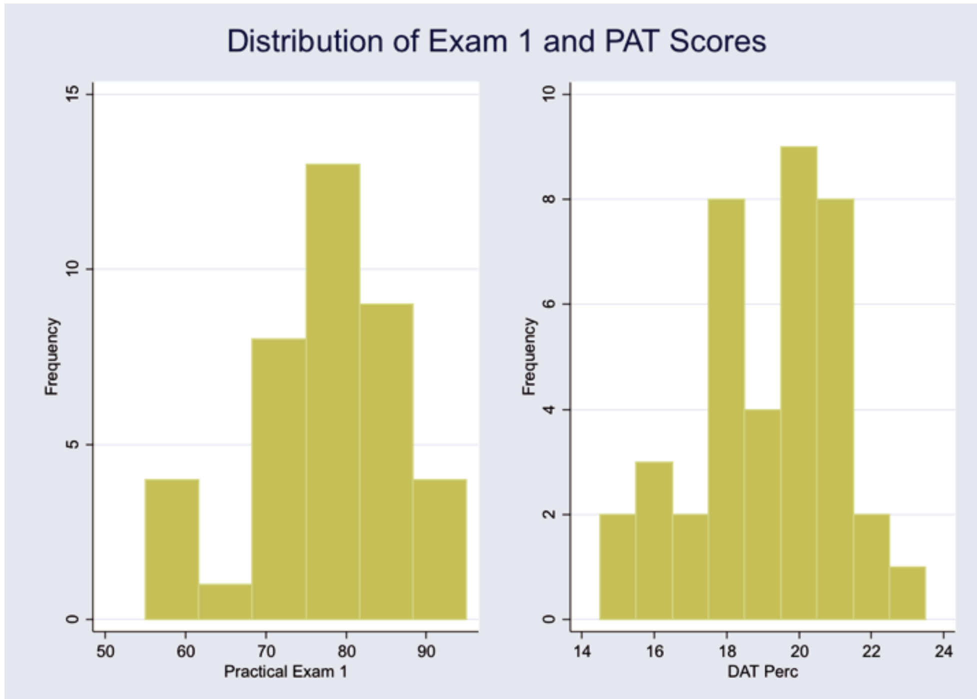

Figure 1. Distribution of Exam 1 and PAT scores

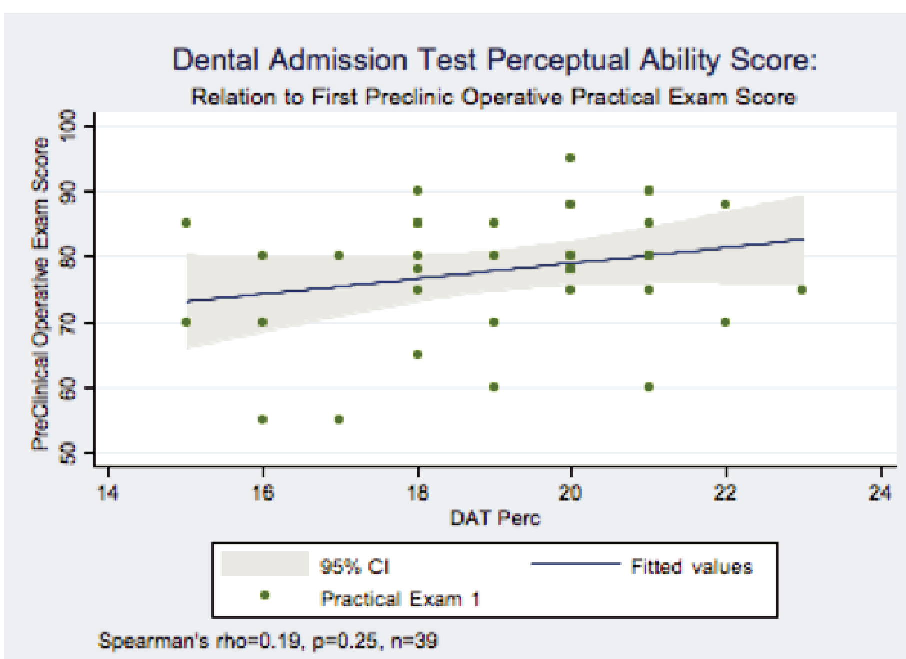

Figure 2. Statistical correlation between students' Exam 1 and PAT scores

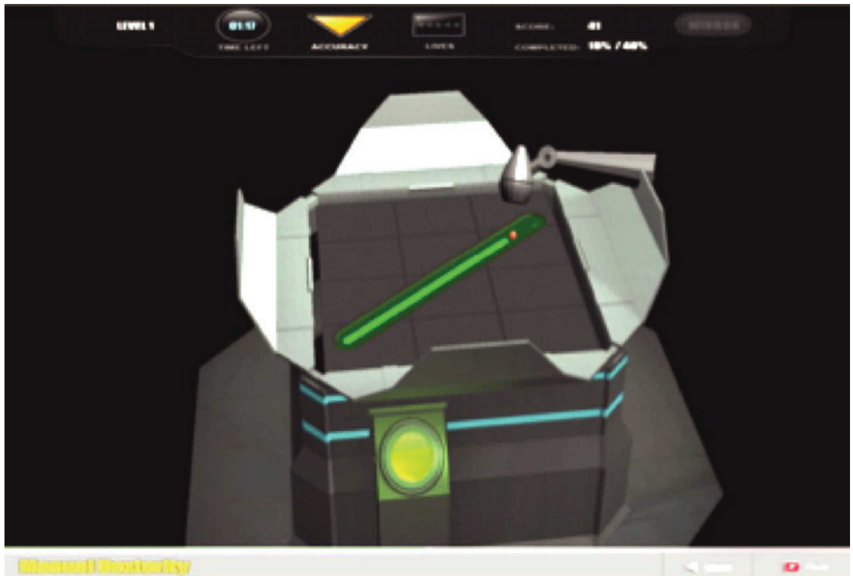

Figure 3. Line exercise: user must remove the green line using the haptic handpiece

Table 1. Statistical correlation between student scores on the simulated haptic carving exercises with Exam 1 and PAT scores

		Exam 1		PAT	
Haptic Exercise		Spearman's rho	p-value	Spearman's rho	p-value
Line	TL	0.16	0.32	0.07	0.66
	TLC	0.16	0.32	0.07	0.66
	AL	0.24	0.14	0.02	0.90
	ALC	0.25	0.13	0.01	0.96
Circle	TL	0.38	0.016*	0.13	0.42
	TLC	0.25	0.13	0.34	0.037*
	AL	0.43	0.006**	0.10	0.54
	ALC	0.17	0.17	0.21	0.20
Mirror	TL	0.31	0.056***	0.05	0.74
	TLC	0.33	0.039*	0.11	0.48
	AL	0.30	0.060***	0.27	0.09***
	ALC	0.30	0.068***	0.26	0.10
Total	TLCT	0.35	0.028*	0.13	0.42
	ALCT	0.34	0.035*	0.21	0.20
	TACT	0.37	0.019*	0.14	0.40

TL: time left; TLC: time left completed; AL: accuracy left; ALC: accuracy left completed; TLCT: time left completed total; ALCT: accuracy left completed total; TACT: time and accuracy completed total

*p<0.10; **p<0.05; ***p<0.01

Discussion

While traditional measures in the dental school admissions process appear to adequately predict academic success in the United States, predictors of success in the clinic and preclinic are less clear and remain elusive. In the past, chalk carving and waxing tests and, presently, the PAT section of the DAT test have been the only objective measures of noncognitive skill development potential available to dental educators. There are currently no reliable means of assessing manual dexterity ability during the admissions process. Recently, virtual reality devices, including haptic devices, have been developed that may have utility for dental educators. The overall aim of this study was to determine whether performance on spatial manual dexterity tests using a force feedback haptic device was correlated with traditional outcomes of the preclinical curriculum and the PAT test.

To our knowledge this is the first report of an association between performance on a haptic manual dexterity device and important preclinical examination scores as well as PAT scores. One goal of this study was to identify those haptic exercises that best predict actual preclinical performance, but another was to explore whether these tests were associated with PAT test scores. These data suggest that performance on the more complex exercises had a stronger association with preclinical performance. These results provide some evidence that a simulation device using haptic force feedback in a virtual

Table 2. Comparison of PAT and Exam 1 scores by success at the two attempts of the three haptic exercises

	PAT	Exam 1
Line 1		
Success (34)	19.2	78.8
Failure (5)	18.8	73.0
Line 2		
Success (36)	19.3*	78.5
Failure (3)	17.0	73.3
Circle 1		
Success (9)	19.2	79.8
Failure (30)	19.1	77.6
Circle 2		
Success (15)	20.0*	80.6***
Failure (24)	18.5	76.5
Mirror 1		
Success (21)	19.4	81.6**
Failure (18)	18.8	74.0
Mirror 2		
Success (27)	19.2	77.4
Failure (12)	18.8	79.6

*p<0.10; **p<0.05; ***p<0.01

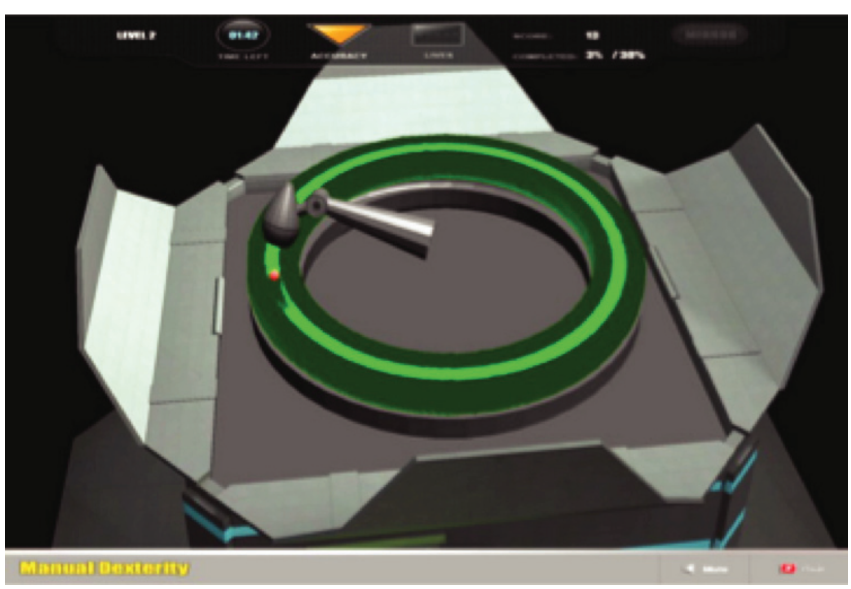

Figure 4. Circle exercise: user must remove the green circle using haptic handpiece

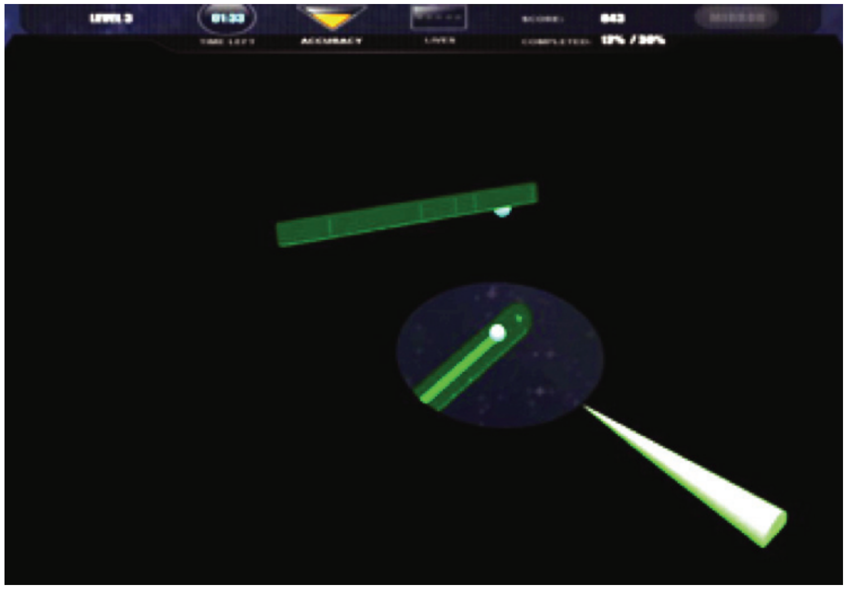

Figure 5. Mirror exercise: user must remove the green line with the haptic handpiece using indirect vision

reality setting may have utility in predicting dental student ability in the preclinic. Further studies are warranted to validate these findings in larger cohorts and to develop new testing and teaching strategies.

We tested dental students on the haptic device using three exercises of varying complexity. The first, the line exercise, was the most straightforward of the three: in it, students were tested on the ability to “remove” structure using a virtual handpiece in a specified time. Accuracy was scored in two ways: by measuring the amount of structure correctly removed and by not going “out of bounds.” Hence, some precision was required for success, as well as completing the exercise in the time allotted. It is perhaps not surprising that, on this relatively simple exercise, we observed no statistical correlations with the measures of accuracy or timing. However, it is surprising that even this simple exercise offered the possibility of failure, and a small number of students did fail. Those who did fail had lower PAT scores than those students who succeeded at the second try. However, no differences in the Exam 1 scores were found between the two groups at the two attempts.

We predicted that the circle exercise would be more challenging to accomplish, and that was indeed the case. Statistically significant correlations were observed between students’ timing and accuracy on this test and their Exam 1 scores and between timing and the PAT scores. Of note was that no single test was a predictor of both the PAT and Exam 1 scores, even though overall success on the second trial of the circle test was associated with significantly higher PAT scores. This finding may suggest that performance on the PAT and performance in operative dentistry preclinic require different aptitudes involving different skill sets. The circle test therefore may be a starting point for new studies aimed at identifying exercises that might capture components of both PAT and preclinic operative test-taking skills. It was

Table 3. Regression table showing results of two models to predict Exam 1 scores using lowest quartile PAT score and mirror exercise success as independent variables

	Model 1	Model 2
Low PAT	-9.004 (2.38)*	-7.054 (1.90)
Mirror	6.331 (2.22)*	75.959 (33.29)**
Constant	79.719	(49.65)**
N	39	39
r-squared	0.13	0.24

Absolute value of t statistics in parentheses.
*Significant at 5%; **significant at 1%

interesting to observe that significant differences in PAT scores between those who failed and those who were successful became apparent during the second and not the first trial of both the line and circle exercises. This may have been due to the students' ability to learn the exercise during the first trial and may possibly differentiate more skilled from slower learners. Future studies will be aimed at measuring the rate of learning these skills and whether they are retained long term. A clear advantage of the haptic computer-assisted exercise over instructor-based feedback with ivorine teeth is the ability to provide a uniform exercise with exact performance scores. This may prove to be a useful feature for tracking students' manual skill development.

We predicted that the mirror exercise would be the most difficult of the three haptic exercises, but it was passed by the majority of students on the first attempt, and in contrast to the other two tests, it was associated with higher PAT scores on the first attempt but not the second. This result may have been due to a design feature of this study: that students were tested on the haptic device after having gained some experience with the handpiece and using indirect vision. The use of indirect vision in the operative course was not new to these students and may in part explain the relatively high level of success most students had with this exercise. One particular measure was significant in our analysis: the measure of time remaining following accurate completion of the mirror exercise. The combination of speed and accuracy using indirect vision ability was highly correlated with Exam 1 success but not PAT scores. This finding may, to a greater extent, indicate skills the students have acquired during the operative preclinic course and, to a lesser extent, spatial reasoning. It was interesting to note that the correlation following the second attempt at the mirror exercise was not significant and may indicate that students were rapidly able to adapt learned skills to this exercise. Future tests on handpiece-naïve students may help to clarify this finding.

We also sought to determine whether the haptic simulator exercises would reveal trends that might help to assess the predictive value of PAT scores. In ranking candidates, admissions officers use the PAT score of the admissions test administered in the United States and Canada in various ways. Past studies have found that the PAT has less predictive ability in the didactic portions of the curriculum and more utility in predicting performance in preclinical and clinical courses.[3,6,7] One aim of the present study was to test whether the haptic manual dexterity exercise, with varying spatial components, could help explain PAT score variance. Indeed, two of the three haptic tests (the line and the circle) resulted in some association with PAT scores, either on the first or second trial. Some specific exercise scores on the more complex exercises (the circle but not the mirror) were more strongly associated with both PAT and Exam 1 scores. Only two individual haptic tests, however, were significantly associated with PAT scores, explaining 10 to 13 percent of the variance of the PAT score in each case. While of potential significance, these findings suggest that more research is needed to determine haptic exercises that more closely capture the abilities measured on the PAT. Still, in this study, at least one of the haptic tests (the mirror) was able to explain an additional 10 percent of the variance when added to the 13 percent attributable to the PAT score. This finding has potentially important ramifications if it is confirmed with other cohorts in prospective studies. A combination test consisting of the PAT and a haptic exercise could potentially be a better predictor of preclinical technique performance than the PAT alone. Caution is needed until such studies are conducted, however, as the American Dental Association's validation studies of the PAT involve data from thousands of students and our study represents a single dental school cohort.

Our results also tend to confirm the utility of the PAT. The result most supportive of PAT score utility was our finding that Exam 1 scores were significantly different when comparing students with high and low PAT scores. Our finding that PAT scores could differentiate students' preclinical performance supports including the PAT score in the admissions process, at least in this small sample of dental students from a single institution. These results are consistent with previous studies that found an association between PAT scores and preclinical outcomes.[6] It remains to be determined whether haptic exercise scores will also have predictive utility for clinical outcomes. These studies, which are under way, should help to further clarify the usefulness of haptic assessments.

Conclusions

The results of this study support a possible role for haptics in dental education, both in short-term practical uses and longer term implementations. One possible short-term practical use of this technology is suggested by the haptic test's ability to detect students likely to have problems on the preclinical course. The early identification of such students would allow for preemptive additional instruction and would, ideally, prevent problems from occurring in the preclinic course or at least diminish them. Future interventional studies are warranted to determine whether early haptic testing helps reduce the number of failures or remediation events. In the longer term, there may be a role for haptics in the testing of dental students prior to admissions. It is conceivable that if certain haptic tests possess sufficient predictive ability for success in preclinic and clinic, broad implementation could play a role in national testing strategies. We speculate that future iterations of virtual reality technologies eventually will become sufficient for wide-scale implementation. As manual dexterity situations become more realistic in the virtual environment, the feasibility of testing actual clinical aptitude in handpiece-naïve students increases.

Our cross-sectional study conducted on a single dental school cohort in the United States found that haptic technology was useful in detecting specified student preclinical performance abilities. There were strong associations between students' performance on certain haptic exercises and their PAT scores and subsequent preclinical operative dentistry examination scores. Some of the haptic exercises when added to the PAT score had greater predictive ability regarding preclinical performance than the PAT alone. Also, these results suggest that students admitted with low PAT scores are at increased risk for poor performance in preclinic. We found that performance on more complex haptic exercises had a stronger association with preclinical performance. Using this information, intervention studies could be aimed at early remediation for those identified by the haptic exercises as being at risk for poor performance in the early preclinic. Future studies will be aimed at refining the haptic test procedure and validating these tests in larger dental school cohorts.

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