Augmented Kinematic Feedback from Haptic Virtual Reality for Dental Skill Acquisition

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Abstract: We have developed a haptic virtual reality system for dental skill training. In this study we examined several kinds of kinematic information about the movement provided by the system supplement knowledge of results (KR) in dental skill acquisition. The kinematic variables examined involved force utilization (F) and mirror view (M). This created three experimental conditions that received augmented kinematic feedback (F, M, FM) and one control condition that did not (KR-only). Thirty-two dental students were randomly assigned to four groups. Their task was to perform access opening on the upper first molar with the haptic virtual reality system. An acquisition session consisted of two days of ten trials of practice in which augmented kinematic feedback was provided for the appropriate experimental conditions after each trial. One week after, a retention test consisting of two trials without augmented feedback was completed. The results showed that the augmented kinematic feedback groups had larger mean performance scores than the KR-only group in Day 1 of the acquisition and retention sessions (ANOVA, $p<0.05$). The apparent differences among feedback groups were not significant in Day 2 of the acquisition session (ANOVA, $p>0.05$). The trends in acquisition and retention sessions suggest that the augmented kinematic feedback can enhance the performance earlier in the skill acquisition and retention sessions.

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Simulation technologies are available today that have a positive impact on the acquisition and retention of clinical skills. Virtual reality (VR) in particular is playing an increasing role in the skills training of health care professionals.[1] At its simplest, virtual reality has been defined as an artificial environment that is experienced through sensory stimuli provided by a computer and in which one's actions partially determine what happens in the environment. Virtual reality simulation systems allow learners to practice the procedure a portion at a time, without risk to a patient. These systems, if validated, could potentially also be used to assess the learner's skills for certification of competence (boards, hospital credentialing, etc.) and for maintenance of skills or acquisition of new techniques once in practice.[2] Several VR programs have been developed to simulate surgical procedures such as the navigation of endoscopes[3] and a surgical simulator for planning and performing repair of cleft lips.[4]

The word "haptic" means relating to, or proceeding from, the sense of touch. Haptics, the study of touch, provides for the incorporation of tactile stimuli into VR systems, allowing the learner to obtain the feel of an invasive procedure.[5] It is generally agreed that this is the most difficult part of teaching an invasive procedure and that improvements in this area of instruction have the potential to steepen the learning curve and improve patient safety. A haptic interface is a device that allows a user to interact with a computer by means of tactile feedback. This feedback is derived by using a manipulator to apply a degree of opposing force to the user along the x, y, and z axes. Haptic interfaces can be used to simulate operations and actions such as deformation and cutting. Three-dimensional haptic devices can be used for applications such as surgical simulation of complex procedures and training unskilled surgeons.

Dental education, of all the health professions, is the discipline that could most benefit from VR since a significant proportion of preclinical dental education is dedicated to teaching psychomotor clinical skills. The haptic VR simulators have been introduced into the dental curriculum as training devices for clinical skill acquisition in several tasks. Training and assessment using these simulators have focused on tactile skills in detecting dental caries[6] and subgingival calculus,[7] as well as hard tissue cutting.[8]

Recently, we have developed a haptic VR system for dental clinical skill training.[9,10] Our prototype focuses on simulating crown preparation and endodontic access opening. The haptic interface provides force feedback to the operator's hand during probing and cutting. Indirect vision was implemented using a computer graphic technique to simulate a mirror. The system is able to extract real-time kinematics that can be used for identification of skill proficiency during tooth preparation.

Two types of information are available to the performer of a procedure: knowledge of result (KR) and knowledge of performance (KP).[11] KR is error information obtained from a comparison of the desired and actual outcomes that may be provided by the performer or by an instructor (e.g., the pulpal depth was 1 mm too deep). KP represents information about the comparison between the desired parameters of the movement with the actual parameters (e.g., whether the handpiece was held perpendicular to the long axis of the tooth when it should have been). Generally, KR and KP facilitate learning because they enable the performer to make appropriate adjustments to the movement on the next trial and increase the likelihood of the desired outcome. Feedback is an important part of skill development. Feedback can be provided at various points in the learning process and in a variety of ways. A large body of research in motor learning[11] and on how various types of information feedback influence the performance, retention, and transfer of motor skills has identified KR (commonly defined as post-response, augmented information about success of the task) as the most critical variable for learning.[12] This research also has provided the basis for the principles governing the provision of information feedback in psychomotor skill learning in dentistry.[13,14] In contrast to the paradigm traditionally used in KR research, an alternative approach utilizes relatively complex movement tasks. The alternative approach has focused on the influence of augmented kinematic feedback or KP, defined as extrinsic, post-response kinematic information about some aspect of the movement pattern.[15,16]

Several types of movement pattern feedback have been shown generally to be effective in enhancing the performance of various skills.[17] However, little or no research has been published about the impact of augmented kinematic feedback on the learning process of dental skill acquisition. The intent of the experiment presented here was to utilize the paradigm developed for augmented kinematic feedback to investigate the role of several variations of movement-pattern feedback on dental skill acquisition compared to retention performance without augmented feedback.

Methods

A randomized controlled trial aimed to investigate the role of several variations of movement-pattern feedback on dental skill acquisition compared to retention performance without augmented feedback. The augmented kinematic information about force utilization and mirror position during tooth preparation was given after the students performed endodontic access opening on the upper first molar using the haptic VR simulation that provided haptic and visual sensation. The augmented kinematic feedback variables examined involved force utilization (F) and mirror views (M). This created three experimental conditions that received augmented kinematic feedback (F, M, FM) and one control condition that did not (KR-only).

We recruited thirty-two sixth-year dental students at Thammasat University School of Dentistry, Thailand. They were not admitted to the study if any of the following criteria were present: left-hand-dominant individual; had prior experience with the simulation; received below 70 percent marks in knowledge assessment of the endodontic access opening; or received below four marks in computer literacy self-assessment.[18] All participants gave their written informed consent approved by the Ethical Review Board of Thammasat University. Stratified random sampling was used to allocate participants to the four conditions that received augmented kinematic feedback, such that each group had five females and three males (Figure 1).

Simulation and Task

We have developed a haptic virtual reality (VR) system for dental clinical skill training.[9,10] The haptic interface provides force feedback to the operator's

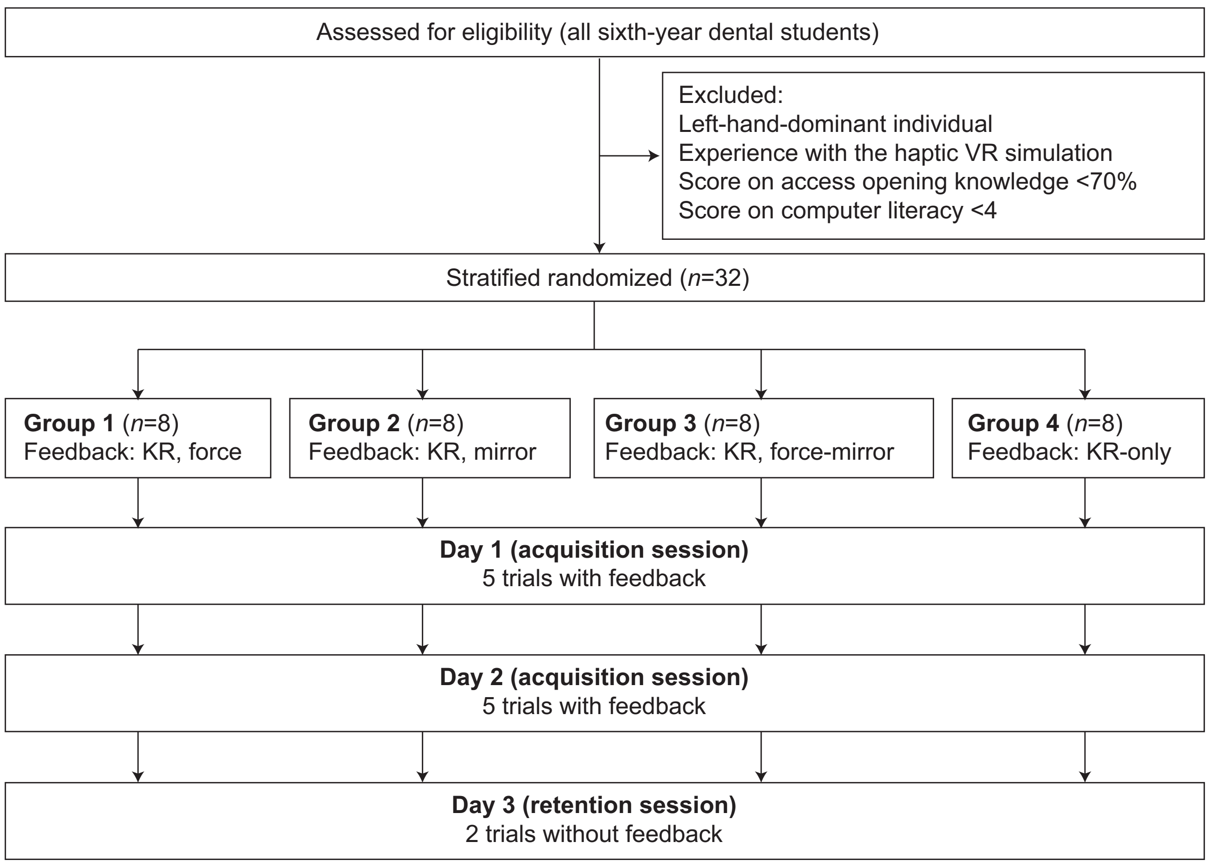

Figure 1. Flowchart of participants through trials

Note: The task for the participants was to perform access opening on the upper first molar with the haptic virtual reality system. An acquisition session consisted of two days of ten trials of practice in which augmented kinematic feedback was provided for the appropriate experimental conditions after each trial. One week after, a retention test consisting of two trials without augmented feedback was completed.

hand during probing and cutting (Figure 2). The participant's task was to perform access opening on the upper right first molar using indirect vision with a haptic VR system. The participants were informed to follow four steps of tooth preparation: Step 1, cut into palatal pulp horn; Step 2, extend the opening laterally to the mesio-buccal canal orifices; Step 3, extend the opening laterally to the disto-buccal canal orifice; and Step 4, extend the opening laterally to the palatal canal orifice. The participant called out each step number, which was manually entered in the system by the investigator (PJ) during tooth preparation.

All preparations were blindly evaluated and graded by the VR system, using six evaluation parameters (visibility of the canal orifices, four axial walls, and pulpal floor). The system assigned to each preparation an overall preparation score between 0 and 18.

Kinematics of the haptic device was collected using the Application Programmer's Interface (API) provided by PHANTOM Omni (SensAble Inc., Woburn, MA, USA). A custom user's performance view program was written by our group to interface with the haptic device. During data collection, the system recorded data associated with the performance process in each step of the access opening including force utilization in x, y, and z axes (x=bucco-lingual direction, y=mesio-distal direction, and z=long axis

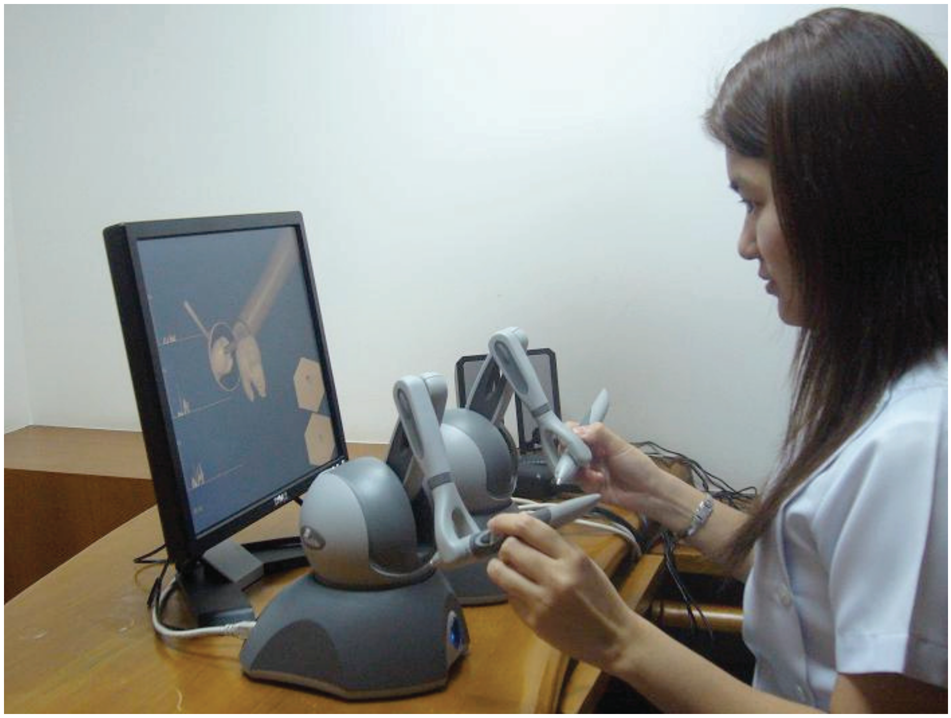

Figure 2. A dental student performing tooth preparation with a haptic virtual reality system

of the tooth) and mirror views used in relation to the tooth. To quantify the extent of bimanual dexterity, a coordination analysis was conducted to evaluate the direct relationship between the mirror positions and the handpiece. Sightline angles were classified into four views. View 1 denotes an acute angle with the left upper part of the sighted surface. View 2 denotes an acute angle with the left lower part of the sighted surface. View 3 denotes an acute angle with the right lower part of the sighted surface. View 4 denotes an acute angle with the right upper part of the sighted surface.

Procedures and Statistical Analysis

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

After the familiarization, the participant performed in acquisition sessions on each of two consecutive days, with a retention session on the third day a week later. A one-week retention test served as our basis for measuring the participants' relatively immediate skill retention, minimizing possible confounding effects from other skills. On the first two days, ten trials of practice, with KR (the overall performance score) after each trail, were completed. The video playback of the student's and expert's performance along with the augmented kinematic feedback was provided for the appropriate experimental conditions after each trial. On the third day, a retention test without kinematic feedback given consisting of two KR-only trials was completed (Figure 3). These trials served as our basis for measuring the participants' relatively permanent capabilities acquired with practice, minimizing possible confounding effects of temporary phenomena present when examining performance in acquisition.

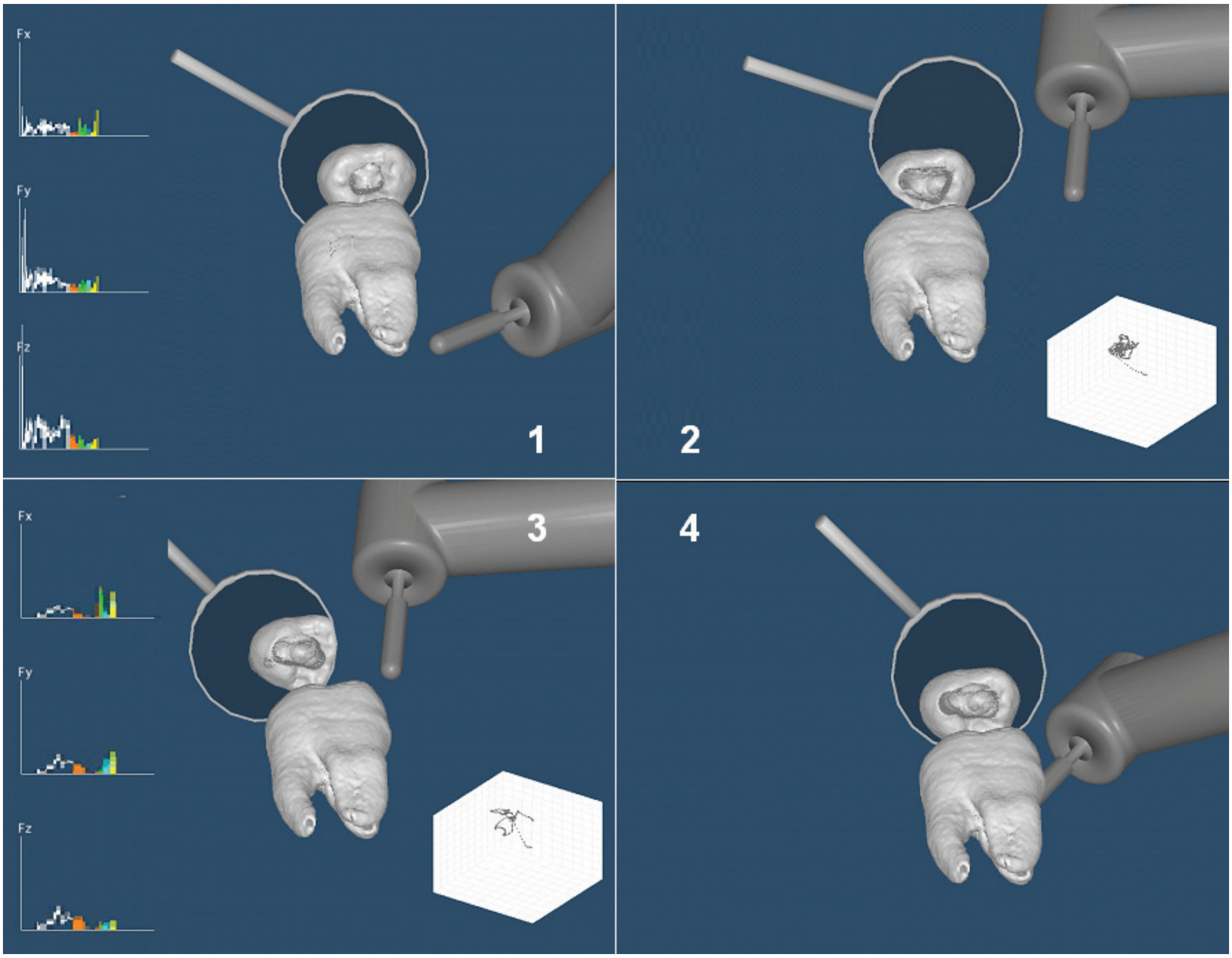

Figure 3. Screen shots of the VDO playback of student performance and augmented kinematic feedback of each group

Note: Groups were as follows: group 1, force (upper left); group 2, mirror (upper right); group 3, force and mirror (lower left); and group 4, KR-only (lower right). Force utilization was presented as three graphs in the x, y, and z axes (x, mesio-distal direction; y, bucco-lingual direction; and z, long axis of the tooth). The mirror view used was tracked from the relationship between the mirror positions and the handpiece.

The overall preparation score (S) was taken as the main dependent variable reflecting success in learning outcome. A one-way analysis of variance (ANOVA) was conducted on the first trial to identify the initial differences among the four groups. For statistical analysis of the acquisition and retention sessions, the average scores of each day were used, and a separate one-way ANOVA with repeated measures on each day was completed. Additional Tukey HSD post hoc tests were applied when significant effects were encountered. In addition, analyses of time to task completion and movement pattern characteristics were also reported to indicate how responses were altered by the various types of augmented kinematic feedback (F, M, FM, KR-only) provided during acquisition. The mean values for time to task completion (T) for each group were compared between the first and the last sessions with dependent t-test. All statistical analyses were performed using SPSS 13.0 (SPSS, Chicago, IL, USA). Statistical significance was defined as a p value less than 0.05.

Results

The performance data of overall access opening score and time to task completion for acquisition (Day 1 and Day 2) and retention (Day 3) sessions are summarized in Table 1.

The mean scores for each group in acquisition sessions (Day 1 and Day 2) are shown in Figure 4. Day 1 (Trials 1 through 5) scores averaged approximately seven points on the first trial and then generally increased with practice throughout the session. For the majority of the trials in this phase, the augmented kinematic feedback groups (F, M, FM) had higher mean scores than the KR-only group. Overall, scores for the FM group were generally the highest, whereas the KR-only group had the lowest mean score and the lowest at the end of the session. Between-group differences were significant: $F(3,28)=3.759$, $p<0.05$, and post hoc (Turkey's HSD) analyses revealed that each of the experiment groups had significantly higher scores than the KR-only group.

The scores on Day 2 (Trials 6 through 10) generally increased. For the majority of the trials in this phase, the augmented kinematic groups had higher mean values than the KR-only group. The differences among feedback groups were not significant, however: $F_{3,28}=1.436$, $p>0.05$.

In the retention session (Trials 11 and 12), the FM group performed most proficiently followed by F and M groups; the KR-only generated the lowest scores. This group effect was significant: $F_{3,28}=4.112$, $p<0.05$. Post hoc (Tukey's HSD) analyses indicated that all augmented kinematic groups were significantly more efficient than the KR-only group. A comparison between experimental and KR-only group indicated that the augmented kinematic feedback condition, as a group, led to more significant effective performance over outcome information feedback. The participants in all groups showed significant reduction in task completion time on Trial 12 compared to Trial 1 ($p<0.05$) (Figure 5).

All groups demonstrated a unique force used pattern in each step of access opening on Trial 12 (retention session), which were not seen in the first trial (Figure 6). In Trial 12, Step 1 (reach palatal canal) required pushing forces mainly along the z axis (long axis of the tooth). Step 2 (reach mesio-baccal canal) required pushing forces mainly along the x axis (buccal-lingual direction). Step 3 (reach disto-buccal canal) required pushing forces mainly along the y axis (mesio-distal direction). Step 4 (return to palatal canal) required pushing forces mainly along the y axis (mesio-distal direction).

Discussion

In this study we used the paradigm developed for augmented kinematic feedback to investigate the role of several variations of movement-pattern feedback on dental skill acquisition compared to retention performance without augmented feedback. In many real-world learning settings, the most effec-

Table 1. Mean and standard deviation values for the overall score and time to task completion analyses of four conditions

		Overall Score (Mean±SD)				Time to Task Completion (sec) (Mean±SD			
Day	Trial	F n=8	M n=8	FM n=8	KR-only n=8	F n=8	M n=8	FM n=8	KR-only n=8
1	1	7.08±0.56	6.01±0.32	7.08±0.54	6.52±0.48	365±22.4	378±25.7	380±24.7	371±31.2
	2	7.75±0.45	7.50±0.36	8.01±0.43	6.52±0.39	301±31.5	322±26.4	317±29.5	329±25.9
	3	9.02±0.37	8.25±0.42	10.03±0.29	7.01±0.37	282±29.8	289±30.8	278±27.8	273±28.4
	4	10.51±0.32	10.75±0.37	13.02±0.27	7.53±0.41	256±24.6	247±31.9	259±24.3	243±26.6
	5	12.48±0.28	12.25±0.25	13.49±0.39	8.51±0.32	224±23.7	219±24.3	220±23.9	217±25.7
2	6	11.01±0.31	10.50±0.33	12.50±0.41	8.02±0.27	218±31.6	220±32.6	204±30.4	208±24.3
	7	13.02±0.42	12.01±0.19	13.97±0.52	10.03±0.41	201±32.5	205±26.4	198±31.5	209±30.4
	8	13.50±0.33	13.02±0.28	15.01±0.29	12.25±0.39	183±24.3	172±24.9	185±32.8	192±32.1
	9	14.02±0.21	14.02±0.23	15.01±0.34	13.01±0.26	167±25.7	171±27.6	165±29.4	173±29.4
	10	15.49±0.34	15.00±0.37	15.98±0.41	13.75±0.33	151±29.8	150±30.9	158±24.6	154±26.4
3	11	15.00±0.29	14.75±0.27	15.50±0.38	12.50±0.27	149±22.4	155±25.7	150±25.5	152±25.4
	12	14.49±0.34	14.75±0.37	15.27±0.41	12.24±0.23	150±31.2	153±27.6	152±24.6	149±26.7

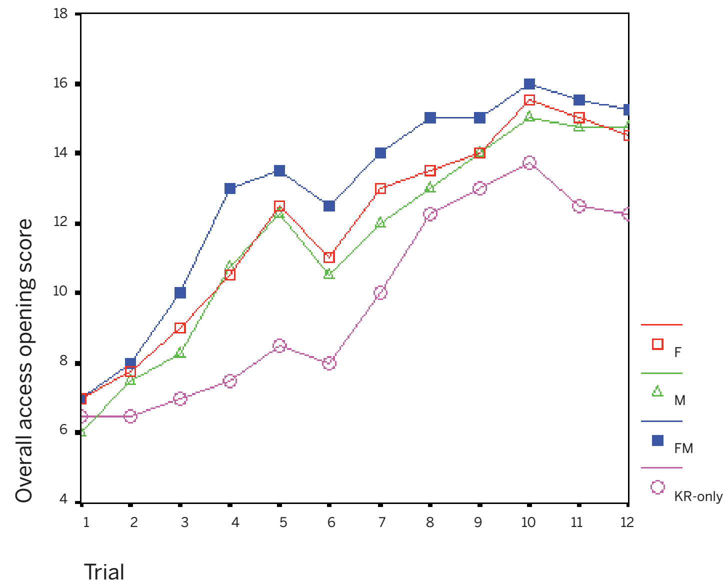

Figure 4. Mean overall access opening score for the four feedback conditions during acquisition (trials 1 through 10) and on the retention test (trials 11 and 12) without kinematic feedback (KR-only)

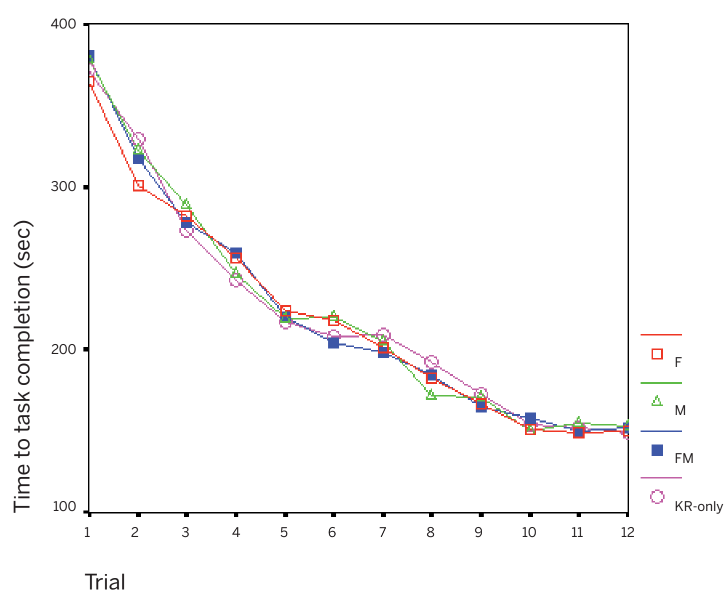

Figure 5. Mean time to task completion for the four feedback conditions during acquisition (trials 1 through 10) and on the retention test (trials 11 and 12) without kinematic feedback (KR-only)

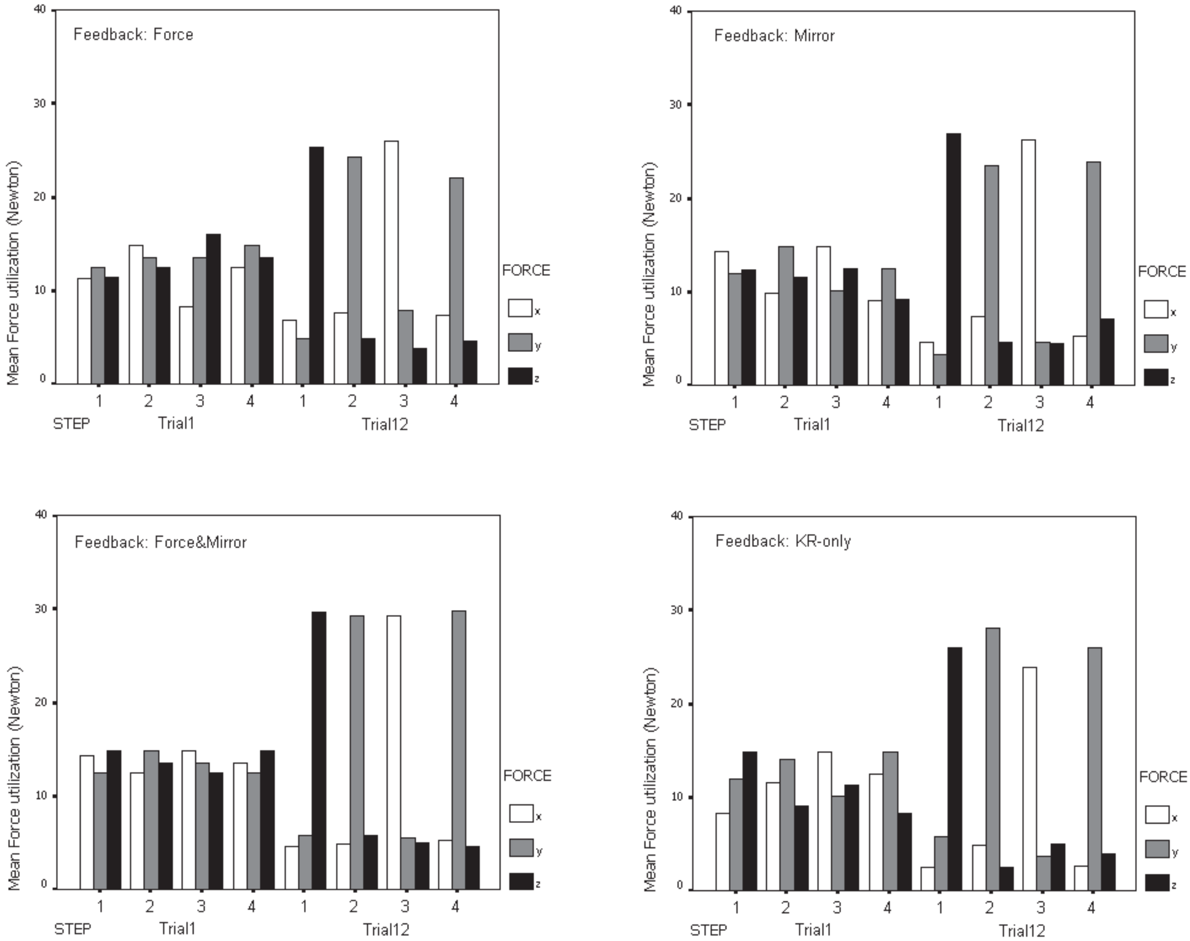

Figure 6. Force utilization for each step (1 through 4) of four feedback conditions in Trial 1 and Trial 12

tive kinematic patterns are relatively well known by the instructor, and kinematic feedback is typically given in practice to bring the learners' patterns in line with these optima. We questioned whether any such kinematic variables that were predictive of effective patterning would be functional as augmented feedback for learning, or whether certain kinematic variables would be inherently more effective as feedback for learning. The strength of the methodology using a VR haptic system for clinical skill training and assessment is that it is not limited to the outcome measurement. It can automatically record associated kinematic data on how students perform each step of the task, e.g., instrument's positions, force, and mirror view used, which are not available in the conventional skill training environments. A limitation of the current simulator is that students interact with the virtual tooth and tool by looking at the computer screen. It would be useful to employ augmented reality technology[19] to achieve visual alignment of the hand with the simulated tool.

Previously, it has been found that augmented feedback aids performance when task-intrinsic feedback (naturally occurring sensory feedback) is not available.[20] In our study, various kinematic characteristics of optimal movement patterns were provided as augmented feedback variables to examine their influence on learning. In general, each of the augmented kinematic feedback variables appeared to be effective in acquisition; after an initial day of practice, all groups that received kinematic feedback performed more proficiently than the KR-only group. The augmented kinematic feedback regarding force and mirror utilization generally enhanced performance over KR-only during the early phase of skill acquisition. This finding is consistent with previous movement-pattern feedback research showing that kinematic variables can function as information feedback to enhance performance in acquisition.[12,13] However, all feedback groups improved almost equally with training at the end of Day 2, indicating that augmented kinematic feedback is not beneficial during the late phase of skill acquisition. We have taken these analyses somewhat further here to examine how kinematic feedback variables enhance the more permanent changes in skill performance, as indicated by performance in retention. All three kinematic feedback variables led to enhanced performance over the KR-only group in the retention test in which kinematic feedback was withdrawn.

This study showed the change in endodontic access opening performance for the novice users of the haptic VR system. Several variables were automatically collected through the real-time kinematics from the haptic VR Application Programming Interface (API), which emphasizes the importance of incorporating haptic VR systems into dental skill training programs. The novice users in this study demonstrated an increase in outcome scores and a reduction in task completion time at the end of the training sessions. As in our previous study,[10] students' learning curves (Figures 4 and 5) showed rapid improvement of the outcome score and task completion time in the first two or three training sessions. This trend is consistent with the results of the study conducted by Wierinck et al.[21] The novice participants in this study demonstrated a unique pattern of force utilization in each step of the access opening at the retention session (Figure 6). This demonstrates the sensitivity of force utilization analysis for distinguishing between different procedure steps. Thus, force utilization analyses are important for distinguishing better between procedure steps for quality training.

In conclusion, the augmented kinematic feedback can enhance the performance earlier in the skill acquisition and retention sessions. Our results also confirm that outcome score, task completion time, and force utilization can be used to represent improvements in the extent of proficiency and/or skill acquisition. Future studies should evaluate dental students with more realistic clinical settings (the ultimate goal of any training program) to gain further insight into the nature of transferability of the motor skill acquired from the haptic VR training system and to identify more applicable variables for patient care.

Acknowledgments

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