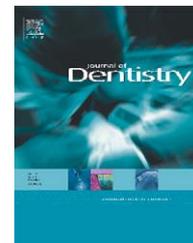


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Process and outcome measures of expert/novice performance on a haptic virtual reality system

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ABSTRACT

Objectives: The goal of dental education is to guide students' development through different stages from novice to competent, eventually resulting in an expert clinician. In this study we sought to identify process and outcome measures of clinical skill performance by comparing novices and experts using a virtual reality (VR) simulation system developed by our group. **Methods:** Ten novices (fourth-year dental students), and ten experts in prosthodontics performed a crown preparation task with a haptic VR that provided force feedback to the operating tool while interacting with the virtual tissue/organ. For each step of the crown preparation, the system automatically recorded data associated with performance process including time to task completion (T), force used (F), and angulations (A) of the bur. The preparation outcome (O) scores were graded by an expert in the field. An independent t-test was conducted on all dependent variables (F in x-, y-, z-axes; A in zy, zx, xy planes; T and O) between experts and novices.

Results: Experts performed significantly better than novices ($p < 0.05$) as shown by greater O. Expert T was significantly less than that of novices ($p < 0.05$). Instrument A as well as F used were significantly different in almost all preparation steps in both groups ($p < 0.05$). **Conclusion:** This study clearly demonstrated the ability of outcome and process measures to distinguish between novice and expert performance in crown preparation using a haptic VR system.

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1. Introduction

Rapid growth has occurred in the areas of distance learning, interactive telecommunications, computer-assisted instruction, and computer simulations. The use of simulation has been proposed as the next major step in the evolution of health science education.^{1,2} The growth of computer hardware and software has led to the development of virtual worlds that support the field of advanced simulation. Virtual

reality (VR) creates virtual worlds using mathematical models and computer programs, allowing users to move in the created virtual world in a way similar to real life. Although used extensively for some time in other fields such as aeronautical training, the technology of VR has only been recently proposed as a powerful tool for the education of health professionals.³ Dental education, of all the health professional schools, is the discipline that could most benefit from VR since a significant proportion of pre-clinical dental

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education is dedicated to teaching psychomotor clinical skills.

Several VR programs have been developed to simulate surgical procedures such as the navigation of endoscopes,⁴ a surgical simulator for planning and performing repair of cleft lips,⁵ a simulation of orthognatic surgery.⁶ Virtual reality is a sophisticated technique for realizing an experience by supplying variable 3D images by computer graphics. In particular, the haptic interface is the cutting edge technology. The word “haptic” means relating to, or proceeding from, the sense of touch.⁷ 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.

The goal of dental education is to guide students' development through different stages from novice to competent, eventually resulting in an expert clinician. Students traditionally devote several years to the acquisition of sufficient fine motor skills to prepare them for entry-level dental practice. Recently, the haptic VR simulators have been introduced into the dental curriculum as training devices for clinical skill acquisition in several tasks. The haptic VR dental simulators that have been developed are: the Iowa Dental Surgical Simulator (College of Dentistry, University of Iowa, Iowa City, IA)⁸ for teaching the tactile skills in detection of dental caries, and PerioSim (Perio-Sim, University of Illinois at Chicago, College of Dentistry, Chicago, IL)⁹ for teaching the tactile skills in the detection of subgingival calculus and a variety of other subgingival topographies. Novint Technologies (Novint, Albuquerque, NM),¹⁰ and Simulife™ Systems (Simulife Systems™, Paris, France),¹¹ for caries detection, cavity preparation and restoration. Of this group, only limited evaluation studies have been reported.^{8,12} These studies suggested that the preliminary “evidence-of-concept” was successful and the system may help students develop necessary dental tactile skills.

Studies have evaluated improvement of performance after training with the haptic VR system in laparoscopic surgery. The current means for evaluating clinical performance and skill acquisition during training are limited to measurement of task completion time and number of errors or a subjective evaluation by an expert.¹³ Task completion time and number of errors were reduced with training. Errors are important to evaluate, but review by an expert is required to identify the errors. Furthermore, the aforementioned measures do not characterize the movements (e.g., speed or distance covered). Moreover, it is not known whether faster is better. The speed-accuracy trade-off is a well-known phenomenon in motor control, in which speed increases cause decreases in accuracy and vice versa.¹⁴ More accurate movements may take more time to complete. Therefore, additional objective measures are needed to quantify surgical performance improvements and differentiate between expert and novice surgeons.

The aim of this study was to assess clinical skill performance of experts and novices by the use of process and outcome measures. Our goal was to identify feasible



Fig. 1 – A dentist performed tooth preparation with a haptic virtual reality system.

variables for better quantifying the extent of clinical skill proficiency. We have developed a haptic VR system for dental clinical skill training (Fig. 1). Our first prototype focuses on simulating crown preparation.¹⁵ Collision detection between virtual patient model and an instrument was calculated to simulate the cutting area and provide force feedback to operator's hand. Indirect vision was implemented using computer graphic technique (described later in Section 2.3). The system is able to extract real-time kinematics which can be used for the identification of skill proficiency during crown preparation. We performed a comprehensive evaluation of all process measures including angulations (A) of the instrument, force used (F), and task completion time (T). The final outcome (O) was evaluated by experts in the field. We hypothesized that expert and novice performances in angulations of the instrument, force used, task completion time and outcome are significantly different. These process and outcome measures provided the foundation for quantifying movement characteristics that can be used for an automatic assessment.

2. Materials and methods

2.1. Participants

Twenty volunteers (10 fourth-year dental students (Novice), ages 20–23 years, and 10 prosthodontics (Expert), ages 35–45 years) were enrolled in this study. Novices had experience using dental handpieces in cavity preparation from the operative pre-clinical course but no prior experience performing crown preparation. Experts had professional training and experience in prosthodontics. All participants were right-handed. None of the participants had received any skill training using a haptic virtual reality system. To assess the computer skills of the participants, a 6-question survey was created based on computer literacy self-assessment.¹⁶ These questions were: (1) name the parts of a computer; (2) use a word processor; (3) get an email address; (4) write and send an email message; (5) search the WWW for specific info; and (6) use a mouse to open and navigate programs. Five-point scales (with 5 on the scale defined as “excellent” and 1 as “none”) were employed. A mean

Table 1 – Metal-ceramic crown preparation.

No.	Preparation steps	Measurements	Inclination
1	Incisal reduction guide grooves	2 mm	
2	Incisal reduction		Perpendicular to long axis of the tooth
3	Facial (cervical plane) reduction guide grooves	1.2–1.5 mm	Parallel to the long axis of the tooth
4	Facial (incisal plane) reduction guide grooves	1.2–1.5 mm	Follow the normal facial contour
5	Facial (incisal plane) reduction		Follow the normal facial contour
6	Facial (cervical plane) reduction including heavy chamfer margin	1 mm width margin	Parallel to the long axis of the tooth
7	Mesial reduction	0.5 mm width chamfer	6° taper
8	Distal reduction	0.5 mm width chamfer	6° taper
9	Lingual alignment groove		Parallel to the cervical plane of FR
10	Lingual (cervical plane) reduction including chamfer margin	0.5 mm width margin	Parallel to the cervical plane of FR
11	Lingual (incisal plane) reduction	1 mm	

rating of lesser than 4 in each question was set as the threshold for the exclusion criteria. All participants rated themselves as “4” or greater in all questions.

2.2. Experimental protocol

All participants were briefly instructed on the use of the system and the requirements of tooth preparation. 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 5 min. During this familiarization or “warming-up” period, the participant was allowed to ask questions and receive further verbal explanation and suggestions from the investigators. After the familiarization, the participant performed two trials of the task while data were not acquired. The third trial was used for data analysis.

Their task was to perform tooth preparation for a metal-ceramic crown on the upper left central incisor with a haptic virtual reality system that provided force feedback to the operating tool while interacting with the virtual tissue/organ. A round-tipped taper bur (1mm) was used. The tooth preparation task required that 11 steps be performed as

shown in Table 1. The tooth preparation order was the same for all participants. The task was designed to mimic real crown preparation, and to require coordination of fingers–hands and eyes or quality performance. Although rotation of the tooth model was able, it was not allowed in this experiment. The participants were required to use direct vision on steps 1–6. Steps 7 and 8 were performed under direct and indirect vision. Steps 9–11 were performed under indirect vision only.

2.3. Experimental equipment

We developed VR simulation system that operates on a HP Pavilion dv5000 laptop with 1.6 GHz Intel processor and 2 GB of main memory (Fig. 2). The graphics card was nVIDIA GeForce Go 7400 with 256 MB of video memory. We used a PHANTOM Omni haptic device (SensAble Inc., USA) which allowed six degrees of freedom positional sensing and generated three degrees of freedom force feedback with a maximum of 3.3 N. The simulator software was developed with C++, OpenGL, OPCODE, and OpenHaptics SDK (HDAPI).

The system is composed of several components as illustrated in Fig. 3. The simulator contains two separate loops (threads), namely haptic loop and graphics loop, running

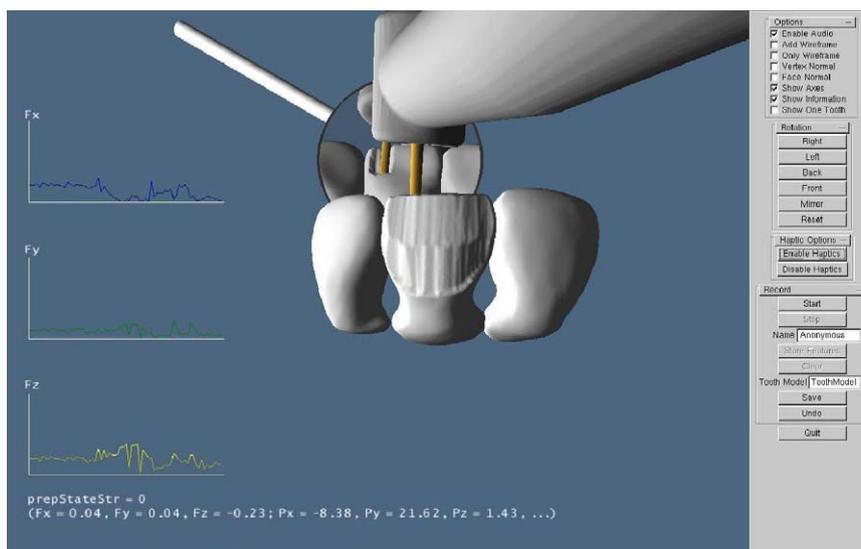


Fig. 2 – Graphic user interface of the haptic virtual reality system.

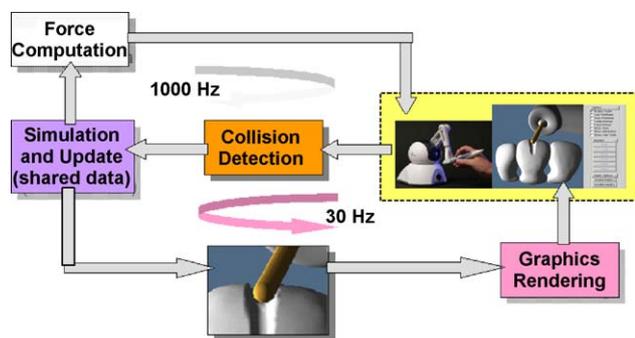


Fig. 3 – A haptic virtual reality system architecture.

at different frequencies. We used surface model to represent teeth and tool for a better visual quality while maintaining a performance of rendering in the graphics loop at a minimum of 30 Hz on our commodity hardware. A dental tool had six degrees of freedom and moved relative to the position and orientation of a haptic probe. We kept collision detection and tooth cutting simulation running along with the haptic loop and still able to maintain 1 kHz update rate all the time for haptic stability. In other words, we computed realistic force feedback and simulated tooth cutting within only 1 ms. This is possible due the fast collision detection and the computational simplicity of surface displacement algorithm that we implement.

There exist data to be shared by the graphics and haptic threads. In order to access and manipulate the data, the threads need to be synchronized with each other to prevent an inconsistent state. However, the haptic thread running at a higher rate should not wait too long for the much slower graphics thread to finish its rendering task. This problem is solved by making fast synchronous calls from graphics thread that block haptic thread temporarily and create a snapshot of shared data for graphics rendering.

Volumetric teeth data was acquired from a volunteer (23-year-old male) who underwent dental implant and gave written consent in accordance with the institutional review board prior to the study. The data was obtained from an i-CAT CBCT (Imaging Sciences International, PA, USA) covering the whole maxilla and mandible. We processed the volumetric data using three-dimensional volume visualization and segmentation software developed by our group.¹⁷ The software allows interactive segmentation and artifact reduction with filtering algorithms such as Gaussian, Median, and Dilation and Erosion filter. We reconstructed a surface mesh from the segmented volumetric output of the segmentation tool using the marching cube algorithm. Since only few teeth were used in our simulator, we chose only three of maxillary teeth. This also helps to increase surface rendering performance by eliminating unwanted polygons. The left maxillary central incisor (Fig. 4b and d) was the main tooth used in the tooth preparation simulation. The mesh of this particular tooth was further subdivided. The final number of triangles for this surface mesh was 38,270.

To simulate tooth cutting in tooth preparation process, we used a surface displacement technique. This technique has

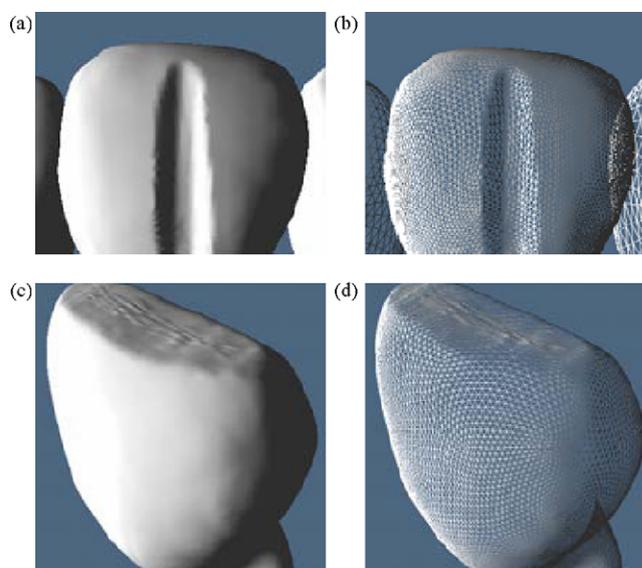


Fig. 4 – Tooth cutting shown in the user interface on the facial surface (a) and incisal surface (c) and their wireframe representation (b and d).

been utilized in many digital sculpting software packages.¹⁸ The displacement process starts when a collision between the tooth and tool is detected. The collision is detected by checking whether the bounding volumes intersect each other or not. We are currently using AABB implementation in Optimized Collision Detection (OPCODE),¹⁹ an opensource C++ library which provides fast and reliable collision detection. Only vertices within the colliding area are used in the computation of their new displaced positions. For each colliding vertex, the distance from itself to the tool in the direction of its vertex normal is computed and the vertex is displaced by the computed distance. Note that this need not be the shortest distance between the vertex and the tool. With this technique, the numbers of triangle faces and vertices are never changed as well as its mesh structure. This is therefore one of the most intuitive approaches to cutting simulation which yields an acceptable result as shown in Fig. 4.

The technique for haptic rendering with force display is based on 3D object. This method requires a group of points distributed over the surface of the probing object. A virtual tool was built as a group of points distributed over the surface model. OPCODE checks all the points on the virtual tool surface against the tooth model. This can prevent tool penetration into the tooth model. When there is a collision between the tool and the tooth, the tool penetrates into the tooth at the area of collision. This penetration results in the computation of the forces to be rendered to the operators in the direction opposite to the movement of the stylus, to avoid further penetration. When the tool is in contact with the tooth surface for the first time, the virtual proxy position (or the position of the tool) (X_o) is stored. When the tool penetrates the surface of the tooth, the position of the tool is changed to X_v . The immersed depth would be the distance from X_o and X_v . When the tool is inside the surface of the tooth, then it is pushed back to the surface of the tooth along the direction of surface normal at the contact point. X_c is the point of contact

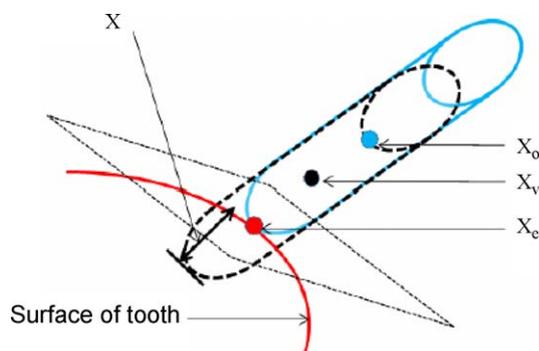


Fig. 5 – Depth of penetration (X) of virtual tool inside the tooth surface.

between the surface of the tooth and the tool as illustrated in Fig. 5. The mirror reflections were implemented using the OpenGL “stencil buffer”. The mirror surface was stored in the stencil buffer. The teeth and the tool were reflected by a scaling transformation and drawn on the mirror surface.

2.4. Measurements

During data collection on crown preparation, we gathered process data sets including elapsed time and kinematic variables with respect to the angulations of the handpiece, and the force used. The preparation outcome scores were graded by one expert in the field who did not participate in the data collection. To assess skill performance of experts and novices, dependent variables were calculated on the basis of process and outcome analyses.

2.4.1. Process analysis

The measures of performance process were based on kinematic measures of the haptic device tip. Kinematics of the haptic device were collected using the Application Programmer’s Interface (API) provided by PHANTOM Omni (SensAble Inc., USA). A custom user’s performance view program was written by our group to interface with the haptic. All postprocessing of data was performed in MATLAB (version 6.5; Mathworks Inc., USA). Variables of interest streamed from the API were position (x , y , z location) of the instrument tip. A local coordinate system was defined for all kinematics: x , y , and z . During data collection, the system recorded data associated with performance process in each step of the crown preparation including time to task completion (T), forces (F) in x -, y -, z -axes^c and angulations of the bur (A) in zx , zy , xy planes^d.

2.4.2. Outcome analysis

The final tooth preparation results were saved. The preparation outcome (O) scores were graded by one expert in the field

^c x (mesio-distal direction), y (facio-lingual direction), and z (long axis of the tooth).

^d zx (right-left angulations against vertical axis), zy (forward-backward angulations against vertical axis), and xy (rotation around vertical axis).

who did not participate in the data collection. The examiner used a haptic VR system, as the measurement could be made using the virtual bur and adjacent teeth. The participant ID (1–20) was used with random order. All tooth surfaces (incisal, facial, mesial, distal and lingual) were evaluated and graded using three evaluation parameters – depth, inclination, smoothness – as assessment criteria. Three-point scales (with 2 on the scale defined as “reference”, 1 as “acceptable”, and 0 as “unacceptable”) were employed. Cutting the adjacent tooth on proximal reduction was considered unacceptable in that step. Thus the maximum score for each surface was 6, and the total maximum score was 30.

2.4.3. Statistical analysis

Group means were calculated for all dependent variables: T , F - x - y - z , A - zy - zx - xy , and O . Subsequently, independent t-tests were used to compare the group means between experts and novices for each measure at confident interval = 95%. All statistical analyses were performed using SPSS 12.0 (SPSS, Chicago, IL, USA).

3. Results

3.1. Outcome analysis

The results showed a significant shorter T for crown preparation in experts (Fig. 6). Expert T (mean = 365.8 s, SD = 29.14) was significantly less than that of novices (mean = 698.60 s, SD = 56.79) ($p < 0.05$). Experts performed significantly better than novices as shown by greater O in all steps of crown preparation (mean expert overall $O = 27.6$, SD = 0.89; mean novices overall $O = 10.6$, SD = 2.19) ($p < 0.05$). As expected, task completion time and outcome successfully distinguished between novice and expert performance.

3.2. Process analysis

Experts demonstrated a unique force used pattern in each step of the crown preparation (Fig. 7). Almost all steps required pushing forces along one axis. Incisal reduction guide grooves (step 1) required pushing forces mainly along the z -axis (long axis of the tooth). Facial reduction guide grooves in both cervical and incisal planes (steps 3 and 4), lingual reduction guiding groove (step 9) as well as mesial and distal reduction (steps 7 and 8) required pushing forces mainly along the y -axis (facio-lingual direction). Incisal, facial and lingual reduction (steps 2, 5, 10 and 11) required pushing forces mainly along the x -axis (mesio-distal direction). The exception was cervical plane preparation on facial surface (step 6) which required pushing forces in z - and x -axes. Novices, on the other hand, did not demonstrate a unique force used pattern and significantly used less main pushing force, as experts did, in all steps of the crown preparation ($p < 0.05$).

Angulations of the bur successfully distinguished between novice and expert performance. Instrument A in zx (right-left angulations against long axis) and zy planes (forward-backward angulations against long axis) (Fig. 8) was significantly different in all steps between experts and novices ($p < 0.05$).

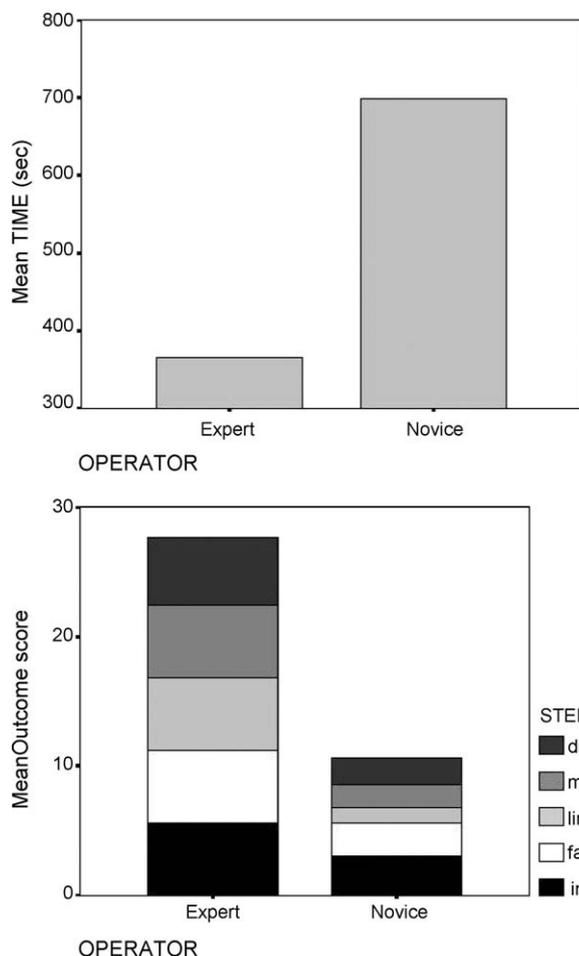


Fig. 6 – Group means for time to task completion (upper) and outcome score (lower) between experts and novices.

Considerably larger differences in zy planes were observed in lingual preparations (steps 9, 10 and 11).

4. Discussion

Regarding the psychomotor skill research evidences, the movement is initiated by a motor program consisting of a series of commands to the appropriate musculature. These commands identify the muscles to be contracted, the order of the contractions, and other parameters that define the nature of the movement. Once the program is selected, it is run off, and the movement is the result.²⁰ Schmidt suggests that in order for the program to be run, the operator must supply the parameters of the proposed movement such as duration, speed, force, and movement size. When these parameters are plugged into the general program, an appropriate movement can be made. Performers play a central role in the control of movements. There are two types of information available to the performer, knowledge of results (KR) and knowledge of performance (KP). KR is error information obtained from a comparison of the desired and actual outcomes the maybe provided by the performer or by an instructor (e.g., the pulpal depth was 1 mm too deep). KP represents information about the compar-

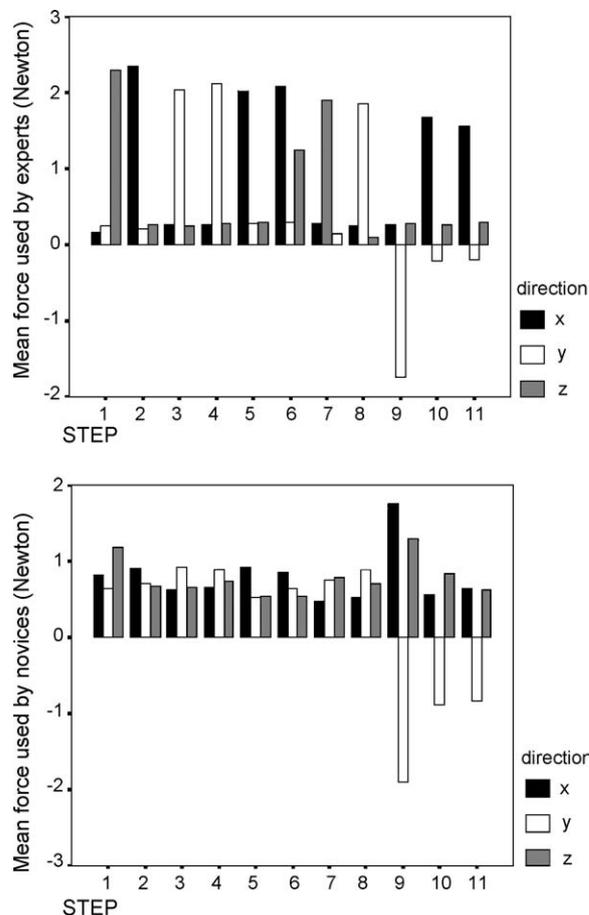


Fig. 7 – Force used in x-, y-, z-axes in experts (upper) and novices (lower).

ison between the desired parameters of the movement with the actual parameters (e.g., was the handpiece 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 will be achieved. Proprioceptors and exteroceptors provide the data that enable individuals to formulate their own KR and KP. Proprioception refers to the sensory feedback that accompanies a movement and includes feedback from the joints, muscles, and skin. Exteroception refers to the sensory feedback from organs such as the eyes and ears that monitor the effects of the movement on the environment. Each time a motor response is made, the relationship between its sensory consequences (proprioceptive and exteroceptive), the initial conditions (e.g., tooth anatomy, location of the tooth in the mouth, posture of the operator, etc.) and the outcome is stored. With practice producing the desired outcome, the operator comes to associate the movement with particular sensory consequences. During the skill acquisition phase, this relationship will be strengthened by the availability of knowledge of result (KR) and the amount of sensory feedback available on each trial. Unlike previous studies that relied on the outcome measurements. Our work focused on the measures of both outcome and process (KR and KP respectively according to the above context).²¹

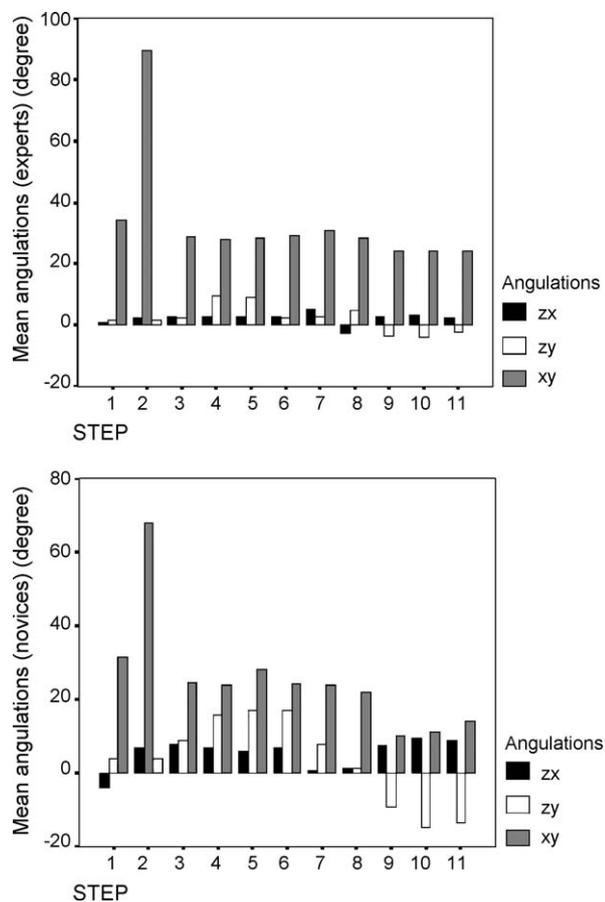


Fig. 8 – Instrument angulations in zx, zy, xy planes in experts (upper) and novices (lower).

Advanced technology simulation is on the verge dramatically affecting health care education. Specifically, virtual reality-based technology allows for more advanced simulation, thereby setting a new state-of-the-art dental simulation. A haptic virtual reality simulator allows practicing tooth preparations in the presence of augmented visual and tactile feedback, resulting in enhanced performance under particular conditions, at least in novices. The VR simulator is a valid and reliable screening device. In this study, all process related data (e.g., force used, position of the bur, angulations of the bur and time to task completion) are automatically recorded by the simulation software. Although volume rendering and tissue segmentation of the tooth model have not been implemented in the current system due to long computation time. Based on a preliminary study of the realism of the simulator, haptic device provides force feedback to the operator similar to working in the real situation.¹⁵ Our results in this study are in line with other research on the differences in preparation outcome and overall performance time between expert and novice. Wierinck et al.²² have published the study that investigating the level of expert performance on preparation score, error score and task completion time in Class II tooth preparation task. Their results showed that the experts in restorative dentistry revealed higher levels of excellence in performance than the novice students, which agreed to the findings of Ericsson,²³ Starkes et al.,²⁴ and Charness et al.²⁵

Studies on evaluating surgical performance and skill acquisition during training revealed that the task completion time and number of errors were reduced with training. Rosen et al.²⁶ evaluated the laparoscopic surgical skills of expert and novice by performed laparoscopic cholecystectomy on pigs. They found that the major differences occurred in force/torque magnitudes at hand/tool interface, type of tool/tissue interactions and time intervals for each tool/tissue interaction and overall completion time. Judkins et al.²⁷ studied objective evaluation of expert and novice performance during three robotic surgical tasks; bimanual carrying, needle passing and suture tying. Their results showed that task completion time, total distance traveled and curvature (straightness of the path) were significantly smaller for experts than for novices, whereas speed was significantly larger for experts than for novices. In our study we found the significant differences in preparation outcome, overall performance time, force used, instrument positions and angulations between experts and novices. Less use of force in novices may lead to increasing time to task completion in each step of the crown preparation. Difference in angulations of the bur used by novices and experts directly affect the shape of the preparation results, as reflected by the final outcome of the tooth preparation.

The strength of the methodology using a VR haptic system for clinical skill assessment is that it is not limited to the outcome measurement as demonstrated in this study. It can automatically record associated kinematic data on how experts or novices perform each step of performing the task, e.g., angulations, and force used, which are not available in the conventional skill training environments. The ability of those process variables that can clearly distinguish between novices and experts skill performance is important for the development of objective scoring criteria that lead to the establishment of rational educational formats. Moreover, such variables are needed to build algorithms for the new generation of improved clinical skill training system that may allow more effective training experience with real-time feedback of skill performance.

In general, the present results clearly demonstrate, within the limitations of this study, the ability of outcome and process measures to distinguish between novice and expert performance using a haptic VR system. All measures (force used, angulations of the instrument, time to task completion and outcome errors) were significantly different between experts and novices. Therefore, these variables have the potential to measure and evaluate clinical skill performance. It is important for dental education to emphasize the teaching and assessing of performance process in addition to the disciplinary content outcome. As for the future work, the parameters on clinical process performance of experts and novices can be modeled using artificial intelligence techniques in order to provide immediate constructive feedback to the trainee during clinical skill practice.

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REFERENCES

1. Plasschaert AM, Wilson NH, Cailleateau JG, Verdonshot EH. Opinions and experiences of dental students and faculty concerning computer-assisted learning. *Journal of Dental Education* 1995;59:1034-40.
2. Buck GH. Development of simulators in medical education. *Gesnerus* 1991;48:7-28.
3. Smith CD. Simulation technology: a strategy for implementation in surgical education and certification. *Presence Tele-Operators and Virtual Environments* 2000;9:632-7.
4. Maass H, Chantier BB, Cakmak HK, Trantakis C, Kuehnapfel UG. Fundamentals of force feedback and application to a surgery simulator. *Computer Aided Surgery* 2003;8:283-91.
5. Schendel S, Montgomery K, Sorokin A, Lionetti G. A surgical simulator for planning and performing repair of cleft lips. *Journal of Cranio-Maxillofacial Surgery* 2005;33:223-8.
6. Sohmura TH, Hojo M, Nakajima K, Wakabayashi M, Nagao S, Iida T, et al. Prototype of simulation of orthognathic surgery using a virtual reality haptic device. *International Journal of Oral and Maxillofacial Surgery* 2004;33:740-50.
7. Massie TM, Salisbury JK. The phantom haptic interface: a device for probing virtual objects.. *ASME 3rd annual symposium on haptic interface for virtual environment and teleoperator systems*, vol. 1. 1994:295-301.
8. Johnson L, Thomas G, Dow S, Stanford C. An initial evaluation of the Iowa dental surgical simulator. *Journal of Dental Education* 2000;64:847-53.
9. PerioSim. At: <http://www.uic.edu/classes/dadm/dadm396/ADSreserch/Intro.htm>. Accessed: January 6, 2009.
10. Novint Technologies. At: http://www.home.novint.com/products/medical_dental.php. Accessed: January 6, 2009.
11. Simulife Systems. At: <http://www.list-company.com/company-info/4028809a13dd74c80113ddb5466a3ddf/SIMULIFE-Systems-SAS-Programming-Daily-Software.shtml>. Accessed: January 6, 2009.
12. Steinberg AD, Bashook PG, Drummond J, Ashrafi S, Zefran M. Assessment of faculty perception of content validity of PerioSim, a haptic-3D virtual reality dental training simulator. *Journal of Dental Education* 2007;71:1574-82.
13. Hashizume M, Shimada M, Tomikawa M, Ikeda Y, Takahashi I, Abe R, et al. Early experiences of endoscopic procedures in general surgery assisted by a computer-enhanced surgical system. *Surgical Endoscopy* 2002;16:1187-91.
14. Rose DJ. A multilevel approach to the study of motor control and learning. Needham Heights, MA: Allyn & Bacon; 1997.
15. Rhiemora P, Haddawy P, Dailey M, Khanal P, Suebnukarn S. Development of a dental skills training simulator using virtual reality and haptic device. *NECTEC Technical Journal* 2008;8:140-7.
16. Computer literacy self assessment. At: <http://www.faculty.matcmadison.edu/mchristoffel/mathring/tech/selftest.htm>. Accessed: January 9, 2009.
17. Suebnukarn S, Haddawy P, Dailey M, Cao DN. Interactive Segmentation and three-dimension reconstruction for cone-beam computed-tomography images. *NECTEC Technical Journal* 2008;8:154-61.
18. Bishop N. Sharpconstruct; 2006, Available at: <http://www.sourceforge.net/projects/sharp3d>.
19. Terdiman P. Memory-optimized bounding-volume hierarchies; 2001, Available at: <http://www.codercorner.com/Opcode.pdf>.
20. Schmidt RA. In: Kelso JAS, editor. *More on motor program*. Hillsdale, NJ: Lawrence Erlbaum Associates; 1982.
21. Schmidt RA. Motor control and learning: a behavioral emphasis. Champaign: Human Kinetics Publishers; 1982.
22. Wierinck ER, Puttemans V, Swinnen SP, Steenberghe DV. Expert performance on a virtual reality simulation system. *Journal of Dental Education* 2007;71:759-66.
23. Ericsson KA. Deliberate practice and the acquisition and maintenance of expert performance in medicine and related domains. *Academic Medicine* 2004;79:S70-81.
24. Starkes JL, Deakin JM, Allard F, Hodges NJ, Hayes A. Deliberate practice in sports: what is it anyway? In: Ericsson KA, editor. *The road to excellence: the acquisition of expert performance in the arts and sciences, sports, and games*. Mahwah, NJ: Lawrence Erlbaum Associates; 1996. p. 81-106.
25. Charness N, Krampe R, Mayr U. The role of practice and coaching in entrepreneurial skill domains: an international comparison of life-span chess skill acquisition. In: Ericsson KA, editor. *The road to excellence: the acquisition of expert performance in the arts and sciences, sports, and games*. Mahwah, NJ: Lawrence Erlbaum Associates; 1996. p. 51-80.
26. Rosen J, Solazzo M, Hannaford B, Sinanan M. Task decomposition of laparoscopic surgery for objective evaluation of surgical residents' learning curve using Hidden Markov model. *Computer Aided Surgery* 2002;7:49-61.
27. Judkins TN, Oleynikov D, Stergiou N. Objective evaluation of expert and novice performance during robotic surgical training tasks. *Surg Endosc* 2009;23:590-7.