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Preliminary evaluation of a virtual reality dental simulation system on drilling operation[1]

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Abstract. To evaluate the fidelity of the *i*Dental system and investigate its utility and performance on simulated drilling operations, user studies consisting of objective and subjective evaluations were performed. A voxel-based drilling simulation sub-system in the *i*Dental system was employed for evaluation. Twenty participants were enrolled to take part in the experiments and were divided into two groups: novice and resident. A combined evaluation method including objective and subjective methods was employed. The objective evaluation included two dental drilling tasks: caries removal operation and pulp chamber opening operation. In the subjective method, participants were required to complete a questionnaire to evaluate the fidelity of the system after the operation task. Based on the structured global assessment scales in the questionnaire, the average subjective evaluation scores of the proposed metrics were greater than 4.5, demonstrating that the system operated above medium fidelity. Dentists expressed great interest and positive attitudes toward the potential of the *i*Dental system. The objective evaluation data including time spent and the volume of removed healthy and carious tissue were obtained. Although no significant differences could be found between the two groups, the volume of removed caries and the depth of pulp chamber insertion manifested small standard deviations. Evaluation results illustrated that dentists were willing to use the virtual reality training system. Several future research topics were identified, including increasing the task difficulty, improving the system fidelity and introducing appropriate finger rest points.

Keywords: Dental simulation, virtual reality, haptic, dental drilling, user evaluation, objective evaluation

1. Introduction

The haptic-based virtual reality dental training system is a novel but still-developing teaching tool in dental education. The biggest difference between virtual surgery and traditional methods practised on phantom heads is that virtual surgery not only provides a clean and non-polluting training environment, but also allows users to receive realistic force feedback akin to practice on real teeth [1-4]. Traditional training methods are limited due to a decrease in the availability of extracted teeth for preclinical

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teaching uses. Additionally, the dust generated by drilling teeth during the training process may pollute the environment and be harmful to the students [2]. The emergence of haptic-based virtual dental training systems provides an alternative new way for dental drilling training.

In the past decades, several virtual dental training systems have been developed [1]. The Simodont Dental Trainer (MOOG Inc. & ACTA (Academic Centre for Dentistry Amsterdam), Netherlands) could simulate dental drilling, the removal of tooth decay, the filling of cavities, crown and bridge preparation as well as mirror reflection [5]. The HapTEL system (The Kings College London & University of Reading, UK) allows users to learn and practice procedures such as dental drilling, caries removal and cavity preparation for tooth restoration [2]. The Forsslund system (Forsslund Systems AB, Sweden) has been designed to provide virtual reality training and practice in dental drilling and wisdom tooth extraction [3]. The Virtual Reality Dental Training System (VRDTS) was developed by Novint Technologies in collaboration with the Harvard School of Dental Medicine, designed to use virtual reality technology for cavity preparation and virtual restoration of teeth [3]. The VirDentT system prototype (Ovidius University, Romania) allows users to prepare teeth for ceramic crowns [4]. The VDP (Virtual Dental Patient, Aristotle University, Greece) was designed to acquaint users with tooth anatomy, the handling of drilling instruments and the challenges associated with the drilling procedure [3].

The evaluation of a dental simulation system is important. For the Simodont, both objective and subjective evaluation methods were implemented to investigate whether skills developed in VR were transferrable to reality and to evaluate the perception of reality provided by the Simodont simulator [6, 7]. The results showed that the skills were transferred successfully, and students and teachers were satisfied with the various aspects of the Simodont. Jonathan et al. [2, 8] evaluated the hardware and software of the HapTEL impact on teaching and learning, and concluded that the finger rest, dental tools, software, and collocation among hand, eye and tool should be merited high priority. Forsslund et al. [9] implemented a subjective evaluation of the Forsslund System to verify design decisions and collect input for modifications of future iterations. The authors inferred that the overall feedback was positive in the sense that the surgeons clearly saw the potential of the Forsslund System, and that simulator-based surgical training in the dental field was achievable. Corneliu et al. [10] evaluated the qualities and the use of the VirDenT system, and concluded that it was necessary to create a warning system for the mistakes committed by students and to mimic a finger rest point. Konukseven et al. [11] from Middle East Technical University and Ankara University in Turkey developed a dental simulator to simulate cavity preparation; the authors implemented a performance assessment and determined that the average time spent on cavity preparation was comparable to that in clinic operations.

However, during the collision detection and haptic interaction of the existing simulators, only a single point of the virtual tool tip could interact with the virtual tooth, which was inconsistent with the reality. Most of the simulators were evaluated by either objective or subjective methods.

A prototype of *i*Dental system has been developed by Beihang University, which can simulate cavity preparation to practice drilling, removal of tooth decay, and several other manual dexterity exercises. To evaluate the level of fidelity of the *i*Dental system and investigate its utility and performance on simulated drilling operations, user studies consisting of objective and subjective evaluations were performed by twenty participants from Peking University School and Hospital of Stomatology.

2. Materials and methods

2.1. Hardware and software

The device used for evaluation was the improved prototype of *i*Dental surgical simulator which consisted of two components: hardware and software. As shown in Figure 1, the hardware includes a haptic device, a computer, monitor, and audio speakers which can present stereo sound made by virtual drilling. The haptic device was Phantom Omni (SensAble Technologies Inc., presently owned by Geomagic® Touch™, USA). The configuration of the computer was: Intel (R) Core (TM) 2 2.20 GHz, 2 GB memory, X1550 Series Radeon graphic card (note that no GPU was used).

The function of the software was to provide a platform upon which users can interact with virtual teeth in a virtual environment and implement virtual drilling operation. The *i*Dental system presented a virtual lower mandible with 14 teeth, one of which was the drilling target tooth with carious tissues.

In the drilling process, when the voxel-based tooth model was drilling by virtual bur, the loss of contact in the voxel-based model often caused force discontinuity and system instability. To avoid these problems, a two-layer model-based material removal method was proposed; that is, the voxels of a tooth were removed just when the interior voxels of the bur have overlapped with those tooth voxels. The boundary voxels of a bur are used to detect contact and compute the resistance force, while the interior voxels are used for material removal. After the corresponding tooth voxels are removed, the tooth voxels overlapped by the boundary bur voxels become the new surface of the tooth and the force discontinuity does not occur. Figure 2 illustrates the material removal method.

A finite element model [12, 13] has been widely used to model the mechanical behavior of tooth materials. However, this model is very time consuming and not suitable for highly efficient haptic rendering simulations (i.e. 1 kHz simulation rate). In the *i*Dental system, a simulation-based rendering method was proposed to coordinate the relationship between fidelity and stability. In this method, the position of the virtual tool was governed by the coupling force as well as the grinding force between the virtual tool and other objects in the virtual environment. A coupling force was defined by adding a

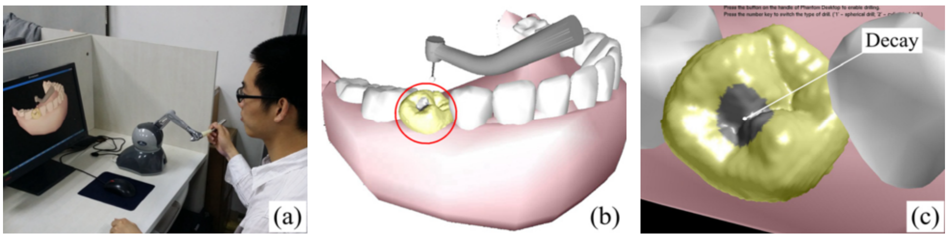

Fig. 1. The training scenario. (a) Simulator setup; (b) Virtual oral environment; (c) Detailed view of virtual carious teeth.

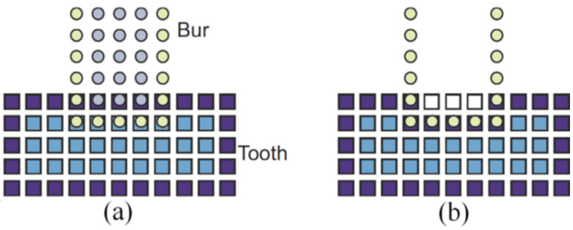

Fig. 2. Two-layer model-based material removal method. (a) Before voxel removed; (b) After voxel removed.

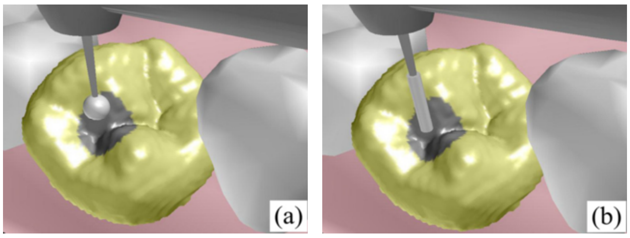

Fig. 3. Virtual drilling bur. (a) Spherical bur; (b) Cylindrical bur.

virtual coupling spring between the positions of the device and the virtual tool. The simulation-based method can overcome the small threshold of damping coefficient in direct rendering and make it possible to achieve maximum fidelity while the device remains stable [14].

One prominent feature of the *i*Dental system is the multi-region contact with which each point of the virtual tool surface can collide with the virtual object with force feedback. Moreover, the shape of virtual drilling bur can switch between a sphere and a cylinder as shown in Figure 3. The spherical bur can be used to drill rapidly and roughly while the cylindrical bur can be used to drill slowly and precisely [14]. In addition to the haptic feedback, the stereoscopic display and sound feedback of the *i*Dental system also enhances the fidelity of the virtual drilling process.

Compared to previous dental drilling simulation systems, the *i*Dental system can simulate real-time collision detection between a target tooth and two different types of drills: the spherical drill and the cylindrical drill. This function enables the human operator to efficiently produce an accurate shape of the cavity by combining the two drills: the spherical drill is used for high-speed mass removal of the decay, while the cylindrical drill is used for fine cutting at the end of the drilling process. Furthermore, by using high-resolution voxels, the volume of removed material can be accurately computed by the *i*Dental system, which provides an important metric for evaluating the quality of surgical operation.

2.2. Participants and methods

To evaluate the dental drilling performance of the *i*Dental system, 20 participants from Peking University School and Hospital of Stomatology were invited to take part in the evaluation process. Participants were divided into two groups: a novice group (ten graduate students, one male and nine females, with less than three years of clinical practice experience) and a resident group (ten resident-level dentists, three males and seven females, with three to ten years of clinical practice experience).

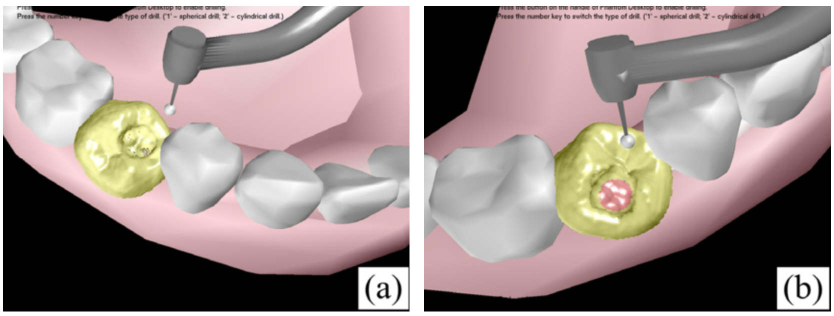

Fig. 4. The drilled holes in the two experimental tasks. (a) After task one; (b) After task two.

Table 1

Questionnaire

	Item No.	Evaluation of Detailed Items	Realism scores						
Haptic fidelity	1	Fidelity of force of touching tooth when machine comes to a halt	1	2	3	4	5	6	7
	2	Stability of touching tooth when machine comes to a halt	1	2	3	4	5	6	7
	3	Fidelity of force feedback when drilling tooth	1	2	3	4	5	6	7
	4	Stability when drilling tooth	1	2	3	4	5	6	7
	5	Fidelity of falling when penetrating pulp	1	2	3	4	5	6	7
	6	Fidelity of braking hand piece when penetrating pulp	1	2	3	4	5	6	7
Graphic fidelity	7	Fidelity of graphic display of caries tooth	1	2	3	4	5	6	7
	8	Fidelity of graphic display of hand piece and bur	1	2	3	4	5	6	7
	9	Fidelity of caries removing	1	2	3	4	5	6	7

In previous studies, a combined method integrating objective and subjective analysis was proposed to evaluate the performance of the dental simulator [15]. In this paper, we adopt this combined method for subjective and objective evaluations of two dental drilling tasks (Figure 4): caries removal operations and pulp chamber opening operations.

The experimental process can be described as follows: first, participants were seated beside the laboratory table in the correct sitting position, holding the stylus of the haptic device with correct grasping posture. Then each participant had 5-10 minutes to freely operate and familiarize themselves with the system; each participant informed the lab assistant when they were prepared to begin the formal experiment. In the formal experiment, participant completed two dental drilling tasks. They were required to drill the target tooth with caries using a drilling speed comparable to that in actual clinical practice. In the operation process, participants were instructed to remove the caries tissue as much as possible while protecting the healthy tooth tissues from removal.

The simulated pulp chamber opening operation was innovative compared to previous dental simulation systems. In this task, the participant was required to drill a deep cavity through the enamel and the dentin until breaking through into the pulp chamber, while minimizing the overshoot displacement of the drill into the pulp cavity; otherwise, the drill may damage the floor of the pulp chamber. This operation task simulated an important dental skill, requiring simultaneous force and motion control. With the assistance of the *i*Dental simulator, participants can experience the feeling of necessary force to break through into the pulp chamger, thus becoming familiar with the drilling experience and controlingl of the overshoot displacement.

Participants were required to protect dental pulp in the caries removal operation, and protect the floor of the pulp chamber from damage in the pulp chamber opening operation. After completing the task, participants informed the lab assistant, who copied the screen and recorded the three performance metrics: the task completion time, the removed volume of healthy tissue and the removed volume of carious tissue [16]. Construct validity was used to determine whether significant differences existed between novices and residents.

Following the two experimental tasks, a subjective evaluation was implemented in which each participant completed a questionnaire based on which the subjective and qualitative evaluation data could be obtained. In the questionnaire, a structured global assessment scale was used to provide an evaluation score on the fidelity of the system [17]. Realism scores on the system included seven levels, i.e. scores from 1 to 7, with 7 referring to high fidelity, 4 referring to medium fidelity, and 1 referring to low fidelity. The system fidelity was further classified into different aspects, including haptic fidelity and graphic fidelity. The detailed items in the questionnaire are illustrated by Table 1. (Note that in order to enhance the efficiency of haptic rendering and the stability of the system, only one tooth can be touched by the drill with force feedback; all other tissues and elements in the virtual oral environment were single graphic rendering and could not provide force feedback.)

For each participant, the data of each benchmark task was measured. For the first task, the following data was recorded: 1) Time to finish the required manipulation; 2) Volume of healthy tissue removed; 3) Volume of carious tissue removed. For the second task, the following data was recorded: 1) Time to finish the required manipulation; 2) Volume of healthy tissue removed; 3) Volume of carious tissue removed; 4) Depth of pulp chamber insertion.

2.3. Statistical analysis

All data was entered into a Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA) spreadsheet, and SPSS software version 18.0 (SPSS Inc., Chicago, IL) was used for statistical investigation. The difference between the clinical experiences of the novice group and the resident group was evaluated by using a two-sample t-test method. A *p*-value of less than 0.05 was considered statistically significant.

3. Results

3.1. Objective analysis

3.1.1. Task one: caries removal operation

For the deep caries removal task, the volume of healthy tissue removed, the carious tissue removed and time spent to finish the task are shown in Figure 5. Moreover, Figure 5(a) illustrates that healthy tissue removed by the novice group was significantly higher than healthy tissue removed by the resident group, indicating that the novices are not as qualified as the residents regarding drilling skills. Also, Figure 5(b) shows that the carious tissue removed by the two groups were nearly equal; we conclude that because the total caries volume was constant and the goal of the task was to remove it, both of the groups were successful in that task. Figure 5(c) illustrates the time spent to accomplish the first task; time spent by novices was significantly less than time spent by residents. By using two-sample t-test method in analysis of the first task, we concluded that there were no significant differences between the time spent by novices and that by residents between the novices and residents ($t(9) = 0.70$, $P > 0.05$).

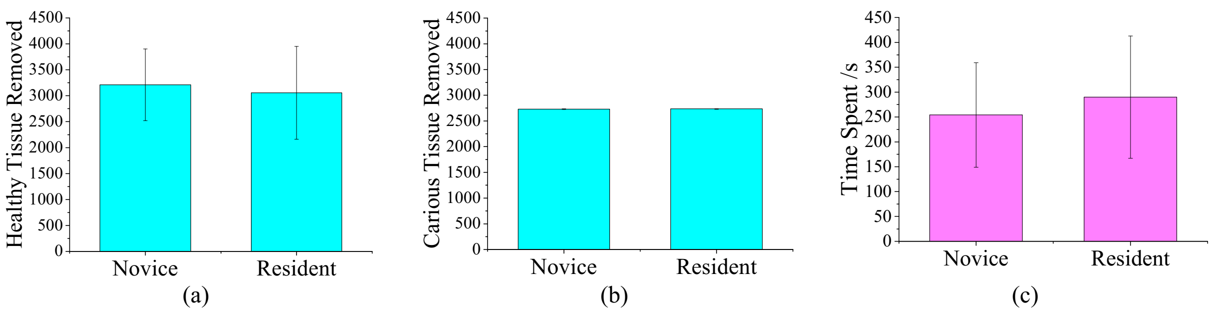

Fig. 5. Recorded data in the first task. (a) Healthy tissue removed; (b) Carious tissue removed; (c) Time spent.

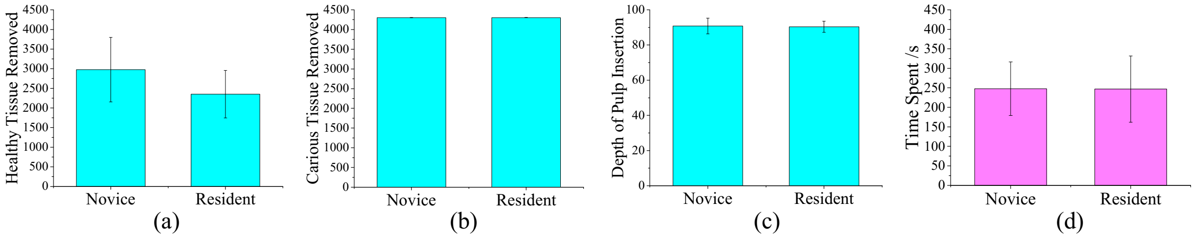

Fig. 6. Recorded data in the second task. (a) Healthy tissue removed; (b) Carious tissue removed; (c) Depth of pulp insertion; (d)Time spent

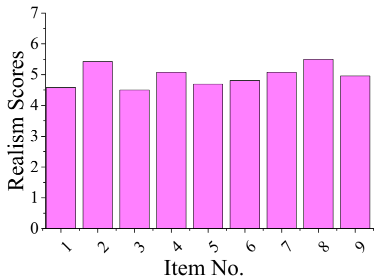

Fig. 7. Average score of each of item in the questionnaire.

3.1.2. Task two: pulp chamber opening operation

For the pulp chamber opening operation, Figure 6 represents the healthy tissue removed, the carious tissue removed, the pulp insertion depth and the time spent to finish the task.

The amount of healthy tissue removed and carious tissue removed are similar to the values in task one. Figure 6(a) illustrates that the healthy tissue removed by the novice group was much higher than the healthy tissue removed by the resident group, demonstrating again that the residents have better clinical practice skills than the novices. Figures 6(b), 6(c), and 6(d) all demonstrate that the carious tissue removed, the depth of pulp chamber insertion and the time cost by two groups were nearly equal. Utilization of a two-sample t-test method for task two demonstrates no significant differences between the novice and resident groups ($t(9) = 0.029$, $P > 0.05$).

3.2. Subjective analysis

Based on the structured global assessment scale provided by the questionnaire, subjective evaluation data on the perceptions of all subjects to the system fidelity are shown in Figure 7. The average scores of all metrics were greater than 4.5, demonstrating that the system fidelity was above the medium fidelity. Therein, graphic fidelity was generally higher while force feedback fidelity was lower. Therefore, more realistic force feedback is required to improve the user's immersive experience. Dentists were positive to the potential of the *i*Dental system and optimistic about its promising future.

In addition to the feedback provided by the questionnaire, participants also proposed many valuable suggestions to the system improvement:

1) Spatial registration precision should be higher. For example, the position and movement distance of the drill and dental bur should be identical, and their movement should be simultaneous.
2) The model of elements in the virtual environment should be more realistic. For example, the material property of current carious tooth model was not identical to a real tooth. The difference

of enamel, dentin and caries was not distinct, and the force feedback received by the user was fairly weak and not realistic.

3) The fidelity of the virtual 3-D space should be further improved, particularly the depth of the virtual space, which was inconsistent with the user's feeling in the real world.
4) The virtual environment should be enriched by providing different types of dental instruments as well as improving the fidelity of graphic rendering.

4. Discussion and conclusions

4.1. Discussion

Based on the results from Figures 5(a) and Figure 6(a), the group of residents displayed slightly better performance than the group of novices. Concerning the removed volume of the carious tissue, no significant differences could be observed between the two groups. The time spent by the group of residents was slightly higher than that of the novices; these results were not consistent with the expectation that the group of residents would manifest significantly shorter performance times than the group of novices. One possible explanation is that the designed tasks are too simple to differentiate the skill level of different participants; more complicated tasks that mimic real clinical situations can be designed in further study.

One possible approach for further study is the addition of a cheek and an upper jaw to partially shield the target teeth, thus requiring the participant to perform the operation in a narrow oral cavity. This can greatly increase the difficulty level of the task, and the experienced dentists may manifest significantly better performances than the novices. Another approach will be to design hand-eye coordination operations that require simultaneous manipulation of a dental drill and a dental mirror to conduct the operation under correct tool postures, which will pose much greater challenges for novices than experienced dentists. In further research, we plan to verify these assumptions by adding new functions to the second generation simulation system, and to investigate the effectiveness of the system and the efficacy of transferring sensorimotor skills from a virtual reality environment to clinical practice.

Based on the structured global assessment scales in the questionnaire, the fidelity of graphic rendering was a significant feature for a high-performance system. Although the scores of the graphic fidelity were relatively high compared to haptic fidelity, none of them exceeded a score of six. Moreover, the majority of participants believed that the graphic fidelity significantly deviated from physical reality. Thus, it is necessary to enhance the fidelity of the graphic display, such as improving the resolution of the graphic model of the teeth and hand piece, adding the upper-jaw and the cheek into the virtual environment, and improving the space alignment precision to enhance depth perception in the 3-D virtual environment.

Based on user feedback in the questionnaire, haptic rendering was another critical technology for the system. As teeth possess complex geometric surfaces with fine geometric features, multi-region contacts between the dental drill and a target tooth must be simulated. Most existing simulators can only simulate single-point contact between the dental tool and a target tooth, i.e., contact between the tip of the tool and the tooth. Although the *i*Dental simulator is capable of simulating multi-region contacts between surgical tools and carious teeth, the participants thought that the force feedback received from the haptic device was not realistic enough. A possible explanation is that the small stiffness (1 N/mm) of the haptic device (Phantom Omni from Geomagic Inc. US.) has limited the fidelity of the force feedback. In order to solve this problem, a new haptic device with higher performance should be used to improve the force rendering fidelity. In addition, various material properties can be added to the virtual oral environment so that all tissues, including the tongue and gingiva, can be manipulated, rather than only the carious tooth.

Based on user feedback in the questionnaire, finger rest point was also an important factor to ensure the accuracy and the stability of the user's hand during the operation. However, because the virtual teeth cannot provide a finger rest point like physical teeth in clinical practice, it is difficult to create a fulcrum as in real world experience, but necessary for the future of dental simulations systems.

4.2. Conclusions

Although the haptic-enabled dental simulator was a promising tool for training, it was unknown what specifications were necessary for an ideal simulator. The results of this experiment have revealed many important lessons to explore. Compared to previous dental drilling simulation systems, several insights can be concluded based upon the experimental results.

First, the reasons leading to insignificant differences between the results of the novice and resident groups could be attributed to insufficient difficulty level of the test tasks. To distinguish the motor skill levels of different participants, increasing the task difficulty becomes necessary. Possible approaches to solve this problem are the addition of a cheek which can partially shield the target teeth, to conduct hand-eye coordination operations with dental drilling and a dental mirror simultaneously in a narrow oral cavity, to conduct the operation under specified tool posture, or to increase the intricacy level of the caries edge, shape, etc.

Second, based on the analysis of the questionnaire, it was determined that a finger support was necessary to maintain the outcome of fine manipulations. Among the existing dental simulation systems, most of them do not provide the finger support. This provided important insight for the design of new generations of dental simulators, in which a finger rest point should be provided to create an accurate clinical practice environment.

Last but not least, more realistic and higher resolution of graphic rendering models should be developed to improve the fidelity of the system. The entire virtual oral environment with maxilla, mandible, gum, tongue, cheek, enamel, dentine, pulp, cementum, et al., should be constructed and able to provide realistic force feedback when users interact with different tissues.

Acknowledgments

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