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The usefulness of a haptic virtual reality simulator with repetitive training to teach caries removal and periodontal pocket probing skills

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Our aim was to evaluate haptic virtual reality (VR) simulation with repetitive training as a tool in teaching caries removal (CR) and periodontal pocket probing (PPP) skills. For the CR simulation, multilayered virtual models composed of tooth substance, caries, and pulp were developed. Seven students completed three training sessions each, which were scored based on the volume of the cut region, the number of instances of handpiece overload, and total cutting time. For the PPP task, we developed a virtual periodontal disease model and 26 students received training in measuring pocket depth. Pocket probing force was measured and proficiency was evaluated. In the CR task, scores for the second and third training sessions were significantly higher than for the first training session. We likewise obtained effective repetitive training results for the PPP task. Our simulator was effective at teaching hand skills for both tasks within short-term evaluation.

Keywords: Haptic virtual reality, Haptic device, Repetitive training, Caries removal skills, Periodontal pocket probing skills

INTRODUCTION

Virtual reality (VR) simulation is an effective tool in skill acquisition because it allows repetitive training with standardized scoring in clinical situations. The effectiveness of VR training has attracted attention in aerospace and medical engineering fields[1-11], and VR already has practical use in flight and surgical simulators.

Traditionally, dental hand skills have been taught using mannequin-based tooth and jaw models[12,13]. The use of extracted teeth for dental training is increasingly difficult because of personal information protection and disease control requirements. Most educational institutions have adopted the use of mannequins for standard training, such as cavity and dental impression preparation.

Current dental mannequins have teeth made of simple plastic, which inadequately replicates the anatomical and mechanical properties of enamel, dentin, and pulp. In addition, repetitive training exercises require the use of many disposable artificial teeth on mannequin. In response to these shortcomings, the dental field has turned its attention to VR simulation[14,15].

Tactile sensations are especially important to dentists because clinical dental procedures require exquisite skill working with a narrow and dark view. Several studies have been published since early 2000 on the use of VR coupled with haptic devices that are able to impart a sense of force feedback to the operator[16-18].

The targeted skills of haptic VR simulation training are caries removal, cavity preparation, periodontal pocket probing, and calculus removal. The development of a haptic VR simulator to teach cutting techniques for caries removal and cavity preparation is essential. Thomas *et al*. have developed a haptic VR training simulator to teach hand skills for caries detection[19]. Simodont® is another haptic VR simulator that has been commercially available to teach cutting skills in recent years. However, available systems have been limited to caries removal and cavity preparation simulation. The lack of versatility for other hand skill training applications is a disadvantage. Suebnukarn *et al*. have compared pre- and post-training results for mannequin-based *versus* VR-based training, using their own haptic VR simulator. They assessed VR training in the hand skills of access opening[20] and access cavity preparation[21] in endodontics, and of crown preparation[22] by both experts and novices in prosthodontics. Steinberg *et al*. have developed PerioSim and also assessed them for faculty perception of content validity of that[23]. However, these studies did not mention the efficacy of repetitive training. Thus, our aim was to evaluate the usefulness of our haptic VR simulator[24] with repetitive training in teaching caries removal and periodontal pocket probing skills.

MATERIALS AND METHODS

Caries removal task

First, we developed a virtual molar model with the material properties of enamel that included a pulp cavity and a carious lesion on the occlusal fossa (Fig. 1). We used a viscoelastic Voigt model that could represent a material having both elasticity and viscosity. By following an experience of dentists, the spring and

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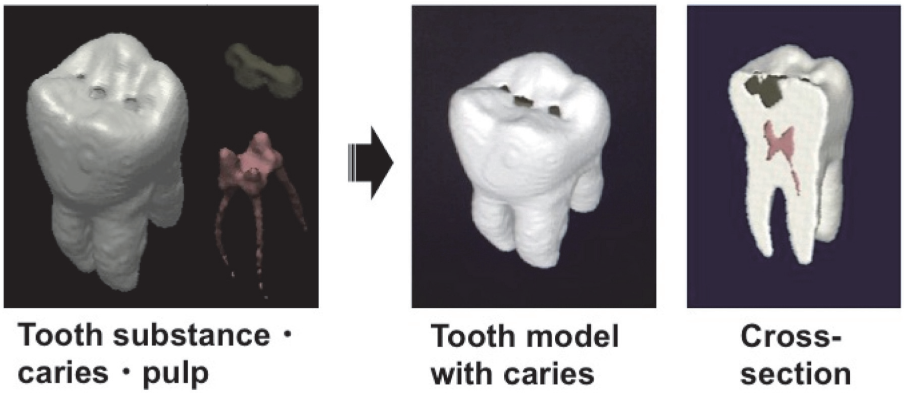

Fig. 1 Computational model for the caries removal task.
Left: tooth substance, caries, and pulp. Right: combined multilayered model and cross section.

damper coefficients for elasticity and viscosity of the carious lesion were empirically set at 0.25 N/mm and 1.0 N・s/mm, respectively, which is softer[25] than the region of the dental hard tissue. The carious lesion was also colored black to clarify the boundary between tooth substance and caries for the operator.

Seven dental students (fourth year students in Osaka University School of Dentistry) with no experience of either cavity preparation or caries removal were randomly selected to perform haptic VR training three times using the virtual tooth model (Fig. 2). The parameters for evaluation were the volume of the section removed from the carious region, V; the number of instances of handpiece overload, N; and the total cutting time, T. To evaluate the training results, we defined the score S based on these parameters as follows:

$$S=V+N+T \quad (1)$$

where the value of V was calculated using the volume of the actual cut section V_{actual} and an pre cut section V_{pre} in the caries region as follows:

$$V=\frac{V_{actual}}{V_{pre}}\times 50 \quad (2)$$

Here, the value of V_{actual} was calculated by subtracting the volume of caries at the end time from the one at the start time.

The overload number N was calculated as follows:

$$N=\frac{N_{thresh}-N_{actual}}{N_{thresh}}\times 25 \quad (3)$$

where the N_{thresh} and N_{actual} are the threshold of the overloaded number and the actual number of the overload 3 N, respectively. In this study, the value of N_{thresh} was set as 1. If the N was less than 0, it was set as 0.

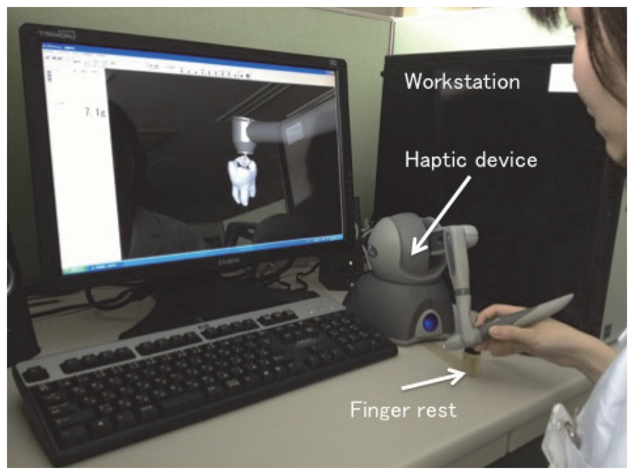

Fig. 2 Scene of running the caries removal task.

Finally, the cutting time T was calculated as follows:

$$T=\frac{(T_{thresh}-T_{actual})}{(T_{thresh}-T_{ideal})}\times 25 \quad (4)$$

where, T_{actual} was calculated by subtracting the start time from the end time. The T_{thresh} and T_{ideal} are the threshold of the cutting time and the ideal cutting time, assigned a value of 600 and 300 s, respectively, with experience of an expert dentist. If the T was over 25, it was set as 25. In this study, each weight of three parameters (V:N:T=50:25:25) was empirically determined.

Periodontal pocket probing task

We scanned the gingiva and dentition in the region of the maxillary right first molar of a jaw model (D51FE-500A-QF, NISSIN, Kyoto, Japan) using a

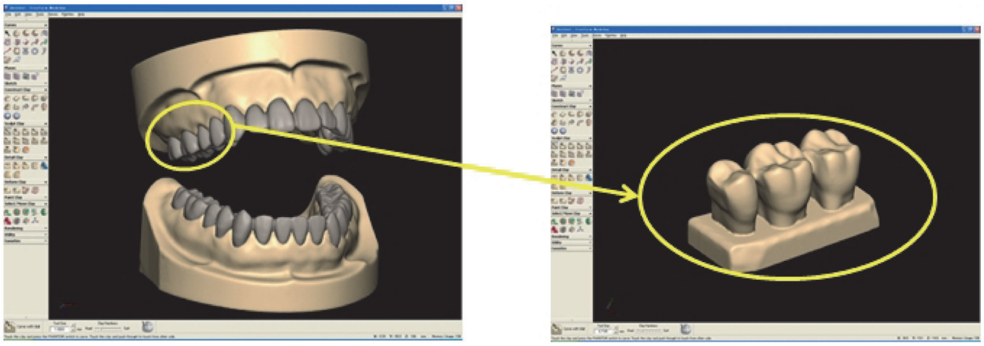

Fig. 3 Computational model for the periodontal pocket probing task.
Yellow circle: periodontal disease modeled by CAD software (flipped vertically).

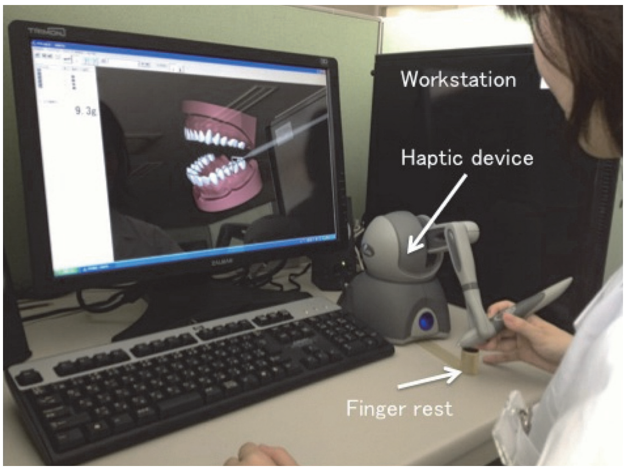

Fig. 4 Scene of running the periodontal pocket probing task.

Table 1 Scores for the periodontal pocket probing task

Probing force p (N)	Score
$0.20<p\leq0.30$	5
$0.30<p\leq0.40$	4
$0.40<p\leq0.50$	3
$0.50<p\leq0.60$	2
$0.60<p$	1

three-dimensional scanner (Rexscan DS2, Solutionix, Seoul, Korea), which resulted in a three-dimensional digitized model. Based on this model, models of the gingiva and dentition were designed using CAD software (FreeFormModeling, SensAble Technologies, Wilmington, MA, USA) and were converted into STL data format. STL data from the maxillary right second premolar, first molar, and second molar were converted to octree data format[24]. Finally, a periodontal pocket model was developed for the proximal surface and cervical areas using CAD software (Fig. 3).

Twenty-six dental students (fourth year students in Osaka University School of Dentistry) with no prior experience in periodontal pocket probing were randomly selected to train using the haptic VR simulator. Students performed depth measurement training for 3-mm periodontal pockets in the central buccal region (Fig. 4). In pre-training, students performed five measurements of pocket depth, and probing forces were recorded without being displayed. The haptic device automatically saved the probing force as digital data. In the first step of training students practiced inserting the dental probe to the bottom of the periodontal pockets for five minutes. In the second step of training five measurements of periodontal pocket depth were made with no display of reaction force. After three repetitions of steps one and two, skill acquisition was evaluated by comparison of pre and post training results.

Statistical analysis

In the caries removal simulation, the mean±standard deviation of scoring results for first, second, and third training sessions were evaluated for significant difference using the two-way ANOVA followed by the Tukey-Kramer test, with $p<0.05$ and $p<0.01$ considered significant (SPSS Statistics 18, IBM-SPSS, Chicago, IL, USA).

In the periodontal pocket probing simulation, the mean probing force for five pocket depth measurements was calculated for each student, and the mean±standard deviation was calculated for all students as a group. These results were translated to a score from 1–5 as shown in Table 1. Scores were evaluated using the two-way ANOVA followed by the Tukey-Kramer test, with $p<0.05$ and $p<0.01$ considered significant.

RESULTS

Caries removal task

The scoring results of the first, second, and third training sessions for caries removal are shown in Fig. 5. The mean score after the first training session was 95.3. The mean score after the second training session was 98.9, significantly higher than the first training result. The mean score after the third training session was 98.1, also significantly higher than the first training result. However, there was no significant difference between the second and third session results.

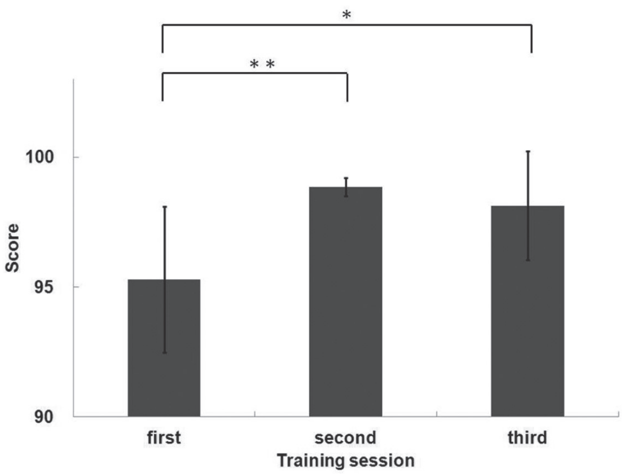

Fig. 5 Training results for the caries removal task. Mean scores of seven students are shown for the first, second, and third training sessions. The vertical bars indicate standard deviations.
*$p<0.05$, **$p<0.01$ Tukey-Kramer test.

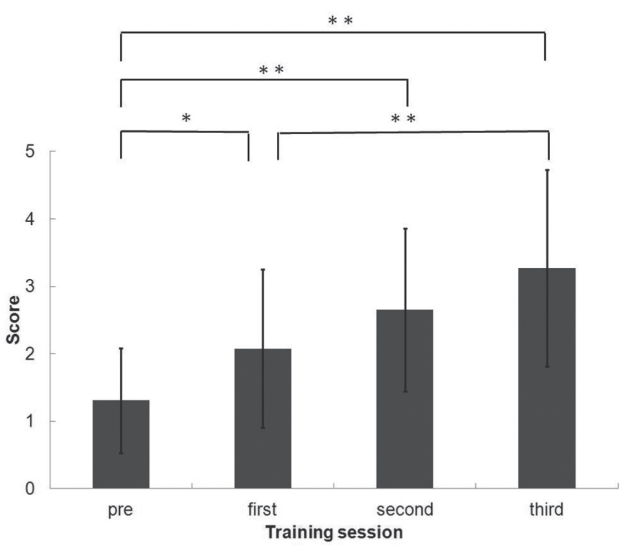

Fig. 6 Training results for the periodontal pocket probing task.
Mean scores of 26 students are shown for pre-training and for first, second, and third training sessions.
*$p<0.05$, **$p<0.01$ Tukey-Kramer test.

Periodontal pocket probing task

The results of mean probing force measurements during pre-training and for first, second, and third training sessions are shown in Fig. 6. The mean scores from the training sessions were significantly higher than the mean pre-training score. The mean score for first, second, and third training sessions was 2.1, 2.7, and 3.3, respectively. The mean was higher with increasing number of training sessions.

DISCUSSION

Conventional haptic VR training simulators have been limited to teaching a single task: caries removal, cavity preparation[26,27], or periodontal pocket probing[23]. Multiple training functions have not been available within a single simulator. One of the reasons for this limitation is the difficulty of modeling force, given the different requirements for operations such as cutting and probing. For example, in the case of a cutting simulation using a rapidly rotating diamond point, the model should take into account the force generated in the direction of rotation. However, such considerations are not necessary for simulated periodontal pocket probing. In this study, it was not necessary for all functions to be implemented in the haptic VR simulator. By creating a function to indirectly send information via parameters set using a human interface, for example "Available" or "Unavailable" for the cutting instruments, we developed a scalable system without the need for re-implementation when adding new tasks. As a result, we successfully used a single VR simulator for multiple training tasks without the requirements of complex force modeling found in conventional simulators.

Our results suggest that our haptic VR training simulator was an efficient tool to teach hand skills of caries removal. One reason for the success of this training may be the use of an adjustable virtual model that allowed us to accurately reproduce hardness differences between carious lesions and healthy tooth substance, as well as cutting sensations that replicated a clinical situation. The actual hardness of carious lesions is case-dependent and acquiring caries removal skills is not easy. Our haptic VR training simulator is adaptable to different learning levels by adjustment of the scoring parameters N_{thresh}, T_{thresh}, and T_{ideal}. Despite the simulator's adjustability, the mean score in the first training session was over 95. However, the scoring criterion for cut volume measured only the volume of the cut region, and not the operator's cutting precision within the carious lesion. Because the fundamental goal of caries treatment is complete removal of the lesion without damage to healthy tissues, scores for excessive and insufficient cutting should be included in future training. Additionally, the current caries removal task does not completely reproduce the clinical situation of using an electrical engine and hand instruments. In an effort to provide more realism we are developing additional tools with reproduction of accurate cutting properties and differences in cutting sensations.

Our VR training simulator was also efficient as a tool to teach periodontal pocket probing skills. In this task, the operator could easily feel the probing force generated by contact with the bottom of the periodontal pockets. Efficient and substantive training could be performed with real-time display of probing forces. Moreover, individual scores increased with each training session. Periodontal pocket probing is a difficult skill to acquire because dentists must measure pocket depth accurately without seeing the bottom of the pocket. If excessive probing force is applied damage to tissues and bleeding may result. Conversely, insufficient probing force results in inaccurate measurements because the tip of probe will not reach the bottom of the pocket. In mannequin-based training, learning to apply correct probing force is especially difficult because the bottom of periodontal pockets is not clearly reproduced. The ideal clinical probing force is 0.25 N[28]. In this experiment, a score of 5 indicated correct probing force. The percentage of students demonstrating correct probing force in the first, second, and third training sessions was 0%, 3.8%, and 26.9%, respectively. These results suggest that repetitive training using a haptic VR training simulator is especially effective in teaching hand skills such as periodontal pocket probing, in which the sense of force is important. Thus, our haptic VR training simulator combined with a computerized tooth model displaying accurate tooth structure and material properties has the potential for expanded use in dental hand skills training. Finger actions of the operator in the VR situation are adjustable by calibrating the initial position, orientation, and scale of VR models in comparison with the actual situation. In addition, VR training involving the tissues surrounding the teeth will become available as models of soft tissue are developed. Furthermore, face models[29] and stereoscopic viewing features are expected, which will improve realism and offer more practical uses.

CONCLUSIONS

We evaluated the efficacy of our haptic VR simulator with repetitive training for caries removal and periodontal pocket probing tasks. Our simulator was effective at teaching hand skills for both tasks within short-term evaluation.

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