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Development of a multi-layered virtual tooth model for the haptic dental training system

Yoshinori YOSHIDA[1,4], Satoshi YAMAGUCHI[1], Yusuke KAWAMOTO[2], Hiroshi NOBORIO[3], Shinya MURAKAMI[4] and Taiji SOHMURA[5]

[1]Department of Oromaxillofacial Regeneration, Osaka University, 1-8 Yamada-Oka, Suita 565-0871, Japan
[2]Technical Group Laboratory Inc., 1-3-7 Shiromi, Chuo-Ku, Osaka 540-6315, Japan
[3]Department of Computer Science, Osaka Electro-Communication University, 1130-70 Kiyotaki, Shijyounawate 575-0063, Japan
[4]Department of Periodontology, Osaka University, 1-8 Yamada-Oka, Suita 565-0871, Japan
[5]Bionic, Co. Ltd., 2-7-14 Higashiawaji, Higashiyodogawa, Osaka 533-0023, Japan
Corresponding author, Satoshi YAMAGUCHI; E-mail: yamagu@dent.osaka-u.ac.jp

A virtual reality (VR) haptic dental training system could be a promising tool for future dental education. One major challenge is to develop a virtual tooth model which similarly reflected a real tooth having multiple layers with different mechanical hardness in each layer. The multi-layered virtual tooth model was successfully constructed in our virtual system. The constructed model allows us to feel tooth cutting which is similar to that with a real tooth. Through a cutting experiment by using the real tooth, a spring coefficient and a damping coefficient of a dental hard tissue were determined 0.8 N/mm and 1.79 Nsec/mm respectively. The feedback force smoothly altered when crossing the border of regions having different mechanical hardnesses. The constructed model introduced in this study could be a promising tool for acquiring dental hand skills in a virtual learning system.

Keywords: Tooth model, Virtual reality, Haptic system, Computer simulation, Dental education

INTRODUCTION

Though dental hand-skill training is one of the most important subjects in dental education, the entire training period has tended to decrease due to limited class schedules. Therefore, the improvement of dental hand-skill training is an essential issue in dental education. In such a case, virtual reality (VR) dental hand-skill training is considered one of the useful candidates for this purpose, because students can use the system at their convenience without having a trainer[1,2)]. To date, numbers of VR dental hand-skill training systems have been introduced. For example, researchers have developed a VR system equipped with a haptic device (Simodont, VOXEL-MAN Dental, Periosim, *etc*.) which allows the operator to feel force during dental treatment[2-6)]. A study indicated that a VR system equipped with a haptic device significantly enhanced the skills of students in tooth cutting tasks[7)]. Thus, the haptic device is now recognized as an excellent tool to apply to a VR education system.

At present we have been developing a new VR haptic dental training system named HAP-DENT. VR dental training system has characteristics that reproduce a mixed reality, including visual, sound and tactile sensations[8-10)]. Though these properties efficiently contributed to raising skills when training dental students, there still remain problems to be solved, such as the inaccuracy of tactile feeling when cutting the virtual tooth, in the VR training system.

Cavity opening is one of the basic tasks in dental treatment. While approaching pulp tissue for endodontic treatment, dentists need to remove both the enamel and dentin. It is commonly understood that the mechanical hardness of enamel and dentin is much higher than that of pulp[11)]. Therefore, dentists generally recognize the region where they are cutting in the individual tooth without seeing but by feeling during treatment. In this context, implementing a different mechanical hardness in each region of the individual virtual tooth is crucial to increasing the realism of tactile feeling during virtual tooth cutting.

The aim of this study was to develop a virtual tooth model which similarly reflected a real tooth with a multi-layer structure having different mechanical hardnesses for the VR haptic dental training system.

MATERIALS AND METHODS

System configuration of HAP-DENT

Our VR haptic dental training system, HAP-DENT, consists of a workstation (xw4600, Hewlett Packard Japan, Ltd., Tokyo, Japan), a haptic device (PHANTOM Omni, SensAble Technologies, Inc., MA, USA), a foot pedal (right part is usable) (CH Pro Pedal, CH Products, CA, USA), and a jig as a finger rest (Fig. 1). A dental turbine and a tooth were constructed in virtual space in this system. Students operate a stylus of the haptic device in six degrees of freedom to control dental turbine movement in the virtual system and to feel a tactile force through the stylus. Students can select a virtual dental diamond point according to the training task among twelve candidates having different tip shapes. The sound changes according to the cutting/non-cutting condition or

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revolution speed of the diamond points in this system. The foot pedal adjusts the revolution speed of the diamond point. The jig for the finger rest provides students with a stable position for operation.

Measurement of cutting force and optimization of model parameters

To avoid higher computational costs, an octree model was applied for tactile detection in this system. An internal node of the octree has up to eight children. By recursively subdividing it into eight nodes, the collision detection point can be searched for faster than with a uniform volume model[8](Fig. 2).

To accomplish efficient collision detection in real-time between a dental hard tissue, pulp and the diamond point, an octree data structure was applied to the virtual tooth model.

In addition to the octree data structure, a Voigt model which can represent a viscoelastic material having both elasticity and viscosity was implemented to reproduce force in the VR system. Here, force F N in the Voigt model consists of the sum of a spring force F_s N and a damping force F_d N:

$$F=F_s+F_d \quad (1)$$
$$F_s=X\times k \quad (2)$$
$$F_d=V\times c \quad (3)$$

where, X mm shows the distance from the surface of the virtual tooth to the tip of the virtual diamond point, V mm/sec shows the motility speed of the stylus, and k N/mm and c N•sec/mm show the spring coefficient and damping coefficient for each material property, respectively.

A virtual cubic model (10×10×10 mm) was prepared by CAD software (Free Form modeling, SensAble Technologies, Inc., MA, USA) and various k value (k=0.0–1.2 N/mm) was given to simulate different mechanical hardness of dental element.

Virtual force through the stylus during the cutting task of the designed cubic model with different mechanical hardness was carried out for 20 times using a material testing machine (EZ-TEST, Shimadzu, Kyoto, Japan, crosshead speed: 0.25 mm/sec) (Fig. 3).

While, to measure the force during cutting a real tooth for comparison a custom-made force measurement system (Fig. 4) was constructed with an extracted native tooth mounted on a six-degrees-of-freedom force detecting sensor device (70M35A25-M50B, NITTA Inc., Osaka, Japan), as previous study[12,13]. Cutting force measurement while cutting an occulusal surface with a rounded diamond point under water irrigation was carried out by using this system.

The damping coefficient was important to attenuate vibration of the spring in detecting the collision of the tool against the model. By substituting an equation (2), an equation (3), and Newton's equation of motion into an equation (1), we obtained the following equation:

$$m\ddot{X}+c\dot{X}+kX=0 \quad (4)$$

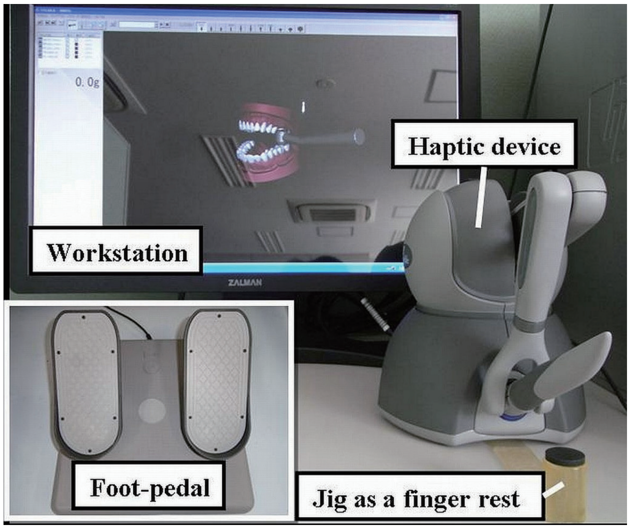

Fig. 1 System configuration of our haptic dental training system.

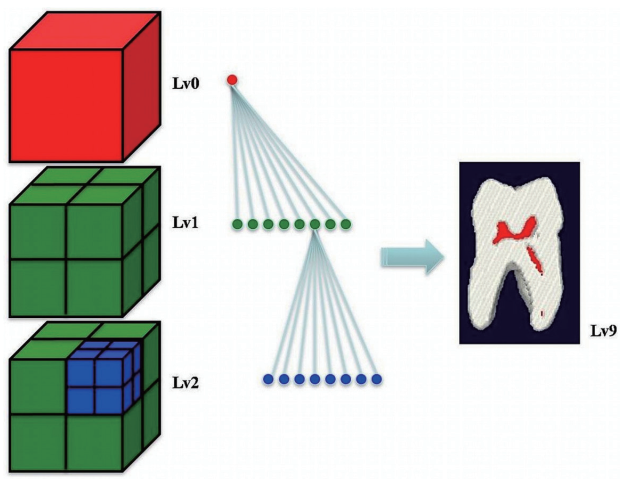

Fig. 2 Volume representation by octree data structure.

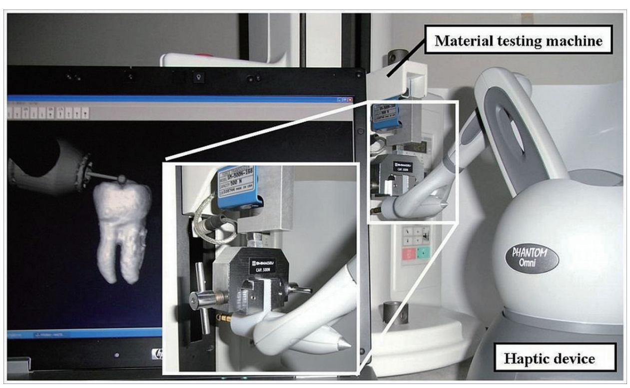

Fig. 3 Experimental setup for measuring the actual force through the stylus during virtual cutting task. Measurement of cutting force of virtual cubic models is carried out as well.

By solving an equation (4) and substitution 1.0 into mass m, c was derived in the following equation:

$$c=2h\sqrt{k} \quad (5)$$

where, h is a damping constant. To realize stable operation, the h value was determined as 1.0 which is a critical dampin[14].

Development of a multi-layer virtual tooth model

To design a tooth model similar to a real tooth, an extracted tooth was measured by micro Computed Tomography (R-mCT, Rigaku, Tokyo, Japan). A three-dimensional virtual tooth model, including crown, root, and pulp, was reconstructed by using volume-rendering software (VG Studio Max 2.0, Volume Graphics, GMBH, Heidelberg, Germany) from the acquired image sequences. The enamel-dentin complex structure and pulp in an individual tooth model was segmented by gray value -19499 in loading data of -16 bit with code (Fig. 5). Parameters k and c in tooth substance or pulp were adjusted according to the value obtained in the above-mentioned study (Materials and Methods 2) to construct the multi-layer virtual tooth model.

To confirm that the constructed model shows multiple mechanical properties in each layer, an EZ-TEST force measurement through the stylus while cutting the constructed virtual tooth model was carried out (30 times, crosshead speed: 0.25 mm/sec).

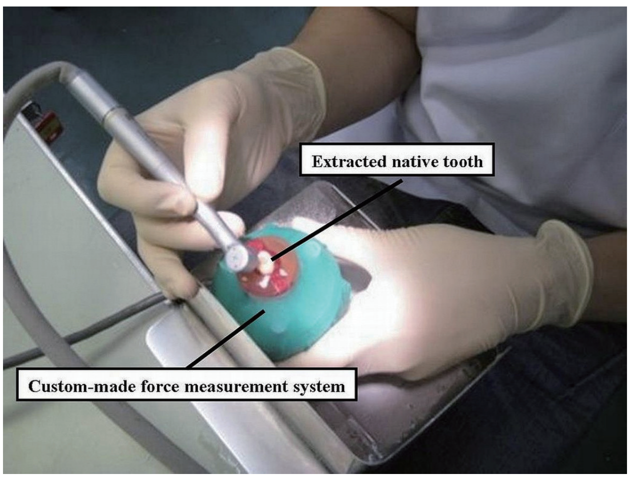

Fig. 4 Custom-made force measurement system with six degrees of freedom.

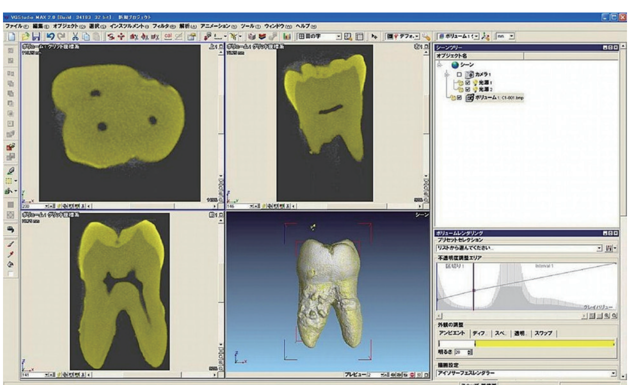

Fig. 5 Region segmentation of dental hard tissue and pulp.

RESULTS

Reducing computational costs is essential to preparing a comfortable working environment in a VR system. For this purpose, an octree model was applied in this system. Consequently, data volume in the virtual tooth octree model shown in Fig. 5 indicated 71 kb, which was relatively low compared with the original stl model (10,241 kb). In addition, a Voigt model was adopted to reproduce the tactile force for cutting a virtual tooth. Therefore, force measurements during the cutting task against the virtual cubic model with different k values were carried out. The results indicated that the cutting force linearly increased with the increase of the k value (Fig. 6). An approximate equation of this alternation is indicated in the following equation:

$$F=0.505k+0.673 \quad (6)$$

Next, to determine the suitable k value for this system force measurement for cutting a real tooth was carried out by using a custom-made sensory system. The results indicated that the average force when cutting a real tooth is calculated as 1.071±0.432 N. (Fig. 7) When applying this value to the obtained equation (6), the k value was calculated as 0.789 N/mm. Therefore, 0.8 N/mm of the k value was utilized for further studies. Because in general pulp is almost a cavity (that is, with no reaction force), the k value for pulp was determined as 0.0. In addition to the k value, the damping coefficient c plays a crucial role to attenuate vibration of the spring force. Equation (5) showed that c of the dental hard tissue in a virtual tooth was 1.79 N•sec/mm when k was

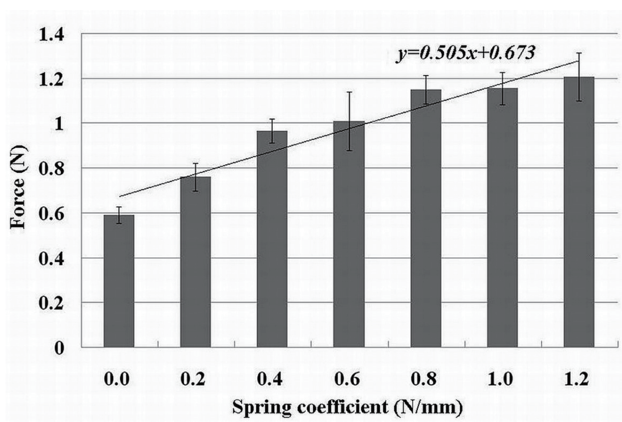

Fig. 6 Force sequence for cutting a virtual cubic model having different spring coefficients k.

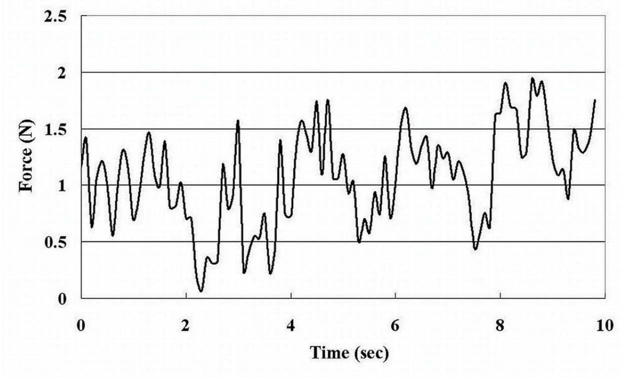

Fig. 7 Force sequence for cutting a real tooth.

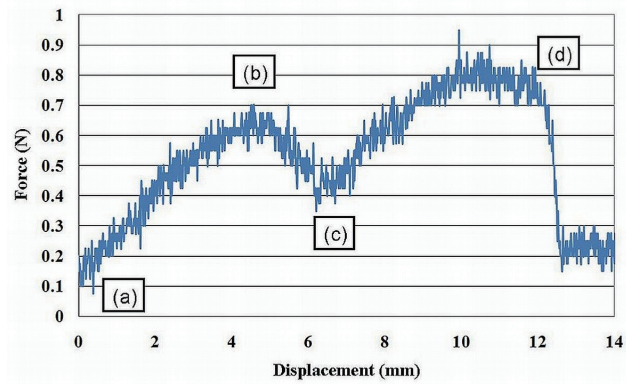

Fig. 9 Force sequence for cutting a multi-layer virtual tooth model.

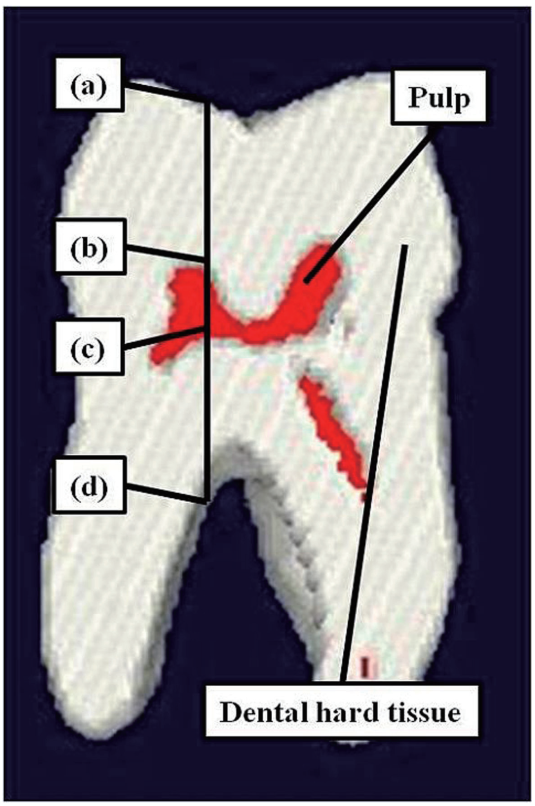

Fig. 8 Dental hard tissue and pulp.

defined as 0.8 N/mm. Thus, we determined the mechanical parameters of each layer in the virtual tooth.

As shown in Fig. 8, a virtual tooth image was successfully designed using volume-rendering software based on micro-CT data. To use this image on our VR dental hand-skill training system, the acquired image data (stl) was converted to a format which includes an octree data structure (dfa). Finally, an exact setting values (the dental hard tissue; k=0.8 N/mm, c=1.79 N･sec/mm, the pulp; k=0 N/mm, c=0 N･sec/mm) for the VR tooth model were implemented.

To evaluate the alteration of the cutting force during the cutting of this constructed VR tooth, force measurements using a material testing machine were carried out. Strikingly, the measured force altered according to the region in the VR tooth model. Fig. 8(a), (b), (c), and (d) correspond to Fig. 9(a), (b), (c), and (d) respectively. In Fig. 9(b), decrease in the force was observed, and it corresponded to the penetration from the dental hard tissue to the pulp at the point (b) in Fig. 8.

DISCUSSION

Though the VR system is recognized as promising for dental hand-skill training in the near future, further improvement of the VR system is still necessary to increase the sense of reality of the tasks[15-18]. Therefore, the construction of a multi-layered tooth model having a different mechanical hardness in each layer was accomplished in this study.

In conventional dental training systems, voxel based models were often adopted to represent a virtual tooth model; however, the computational cost of this model is too high to obtain nimble movements of the virtual tool in a VR system[19-21]. To reduce the cost, an octree based model would be effective in a dental hand-skill training system because the area of collision detection is small in an oral cavity. Consequently, the cost was successfully reduced by applying the model to this VR system.

As a force feedback model, a Voigt model was applied to generate the tactile force in this system by determining the optimal values of k and c. As expected in the equation (2), F_s measured by a material testing machine increased linearly according to the k value in the cubic model system. Interestingly, the measured force (y-intercept) indicated 0.673 N even when the k value was 0.0 (Fig. 6). This could be caused by the friction force originating from the stylus joints of the PHANTOM Omni.

To increase the reality of the tactile sense in the system, tuning the mechanical parameters is one of the most important procedures in VR modeling. A custom-made sensory system was applied to measure the force feedback during native tooth cutting. Based on the measured data, the *k* value of the dental hard tissue was determined as 0.8 N/mm. In addition to this, the *k* value of the pulp was determined as 0.0 because of it being a pulp tissue. It is commonly understood that the *c* value is a parameter to attenuate the fluctuation of the spring in a Voigt model[22]. Therefore, the setting of the *c* value is important for stable movement of the stylus. Consequently, the *c* value was determined as 1.79 or 0 in the dental hard tissue and pulp, respectively, according to equation (5).

To confirm the different tactile sense between objects in the VR system, the alteration of force during the cutting of this constructed VR tooth was evaluated. The measured force as well as tactile sense significantly decreased when the tip of the diamond point moved from the dental hard tissue region to the pulp region in the VR system, which similarly reflected the alteration of the force in a native tooth cut. Importantly, the feedback force smoothly altered when crossing the border of regions having different mechanical hardnesses.

As introduced in this study, a multi-layered tooth model having different mechanical hardnesses was successfully constructed for a VR dental hand-skill training system. Students will be able to learn with more real sense of feeling during the tooth cutting task by using this model tooth in the VR system. Though the constructed tooth model has two layers (the dental hard tissue and the pulp) in this study, the same algorithm could be adopted in a model having three or more layers (*e.g.* enamel, dentin and pulp) by using a computer with higher performance. Since this multiple-layered object model could be adopted not only for teeth but also for any type of biological tissue, the method introduced here to obtain a virtual object could be valuable even in a VR system for medicinal surgical training.

CONCLUSION

A multi-layered virtual tooth model having different mechanical hardnesses on each layer was successfully constructed in our virtual system. The constructed model allows us to feel tooth cutting which is similar to that with a real tooth. The constructed model introduced in this study could be a promising tool for acquiring dental hand skills in a virtual learning.

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