Development of Human Interface Software in our Dental Surgical System based on Mixed Reality

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ABSTRACT

In this paper, we develop a dental surgical system based on mixed reality, which a dental doctor can scrape a concave tooth with complicated shape by a bar located at the tip of turbine. In this system, we represent a tooth and a dental bar as an octree (a set of voxels) and sets of points, respectively. Based on the octree's hierarchical structure in positioning, we quickly detect an intersection between octree-based tooth and point-based bar. Moreover, according to the intersection set, we scrape a tooth by a bar while making force and moment. Finally, many doctors flexibly pick up visual and tactile parameters according to a lot of their experiences. In addition, our system automatically evaluates a student operation against a professional one by comparing their scraping tooth shapes. For this reason, dental students can learn many kinds of surgical operations on demand via PC and internet.

Keywords

Mixed reality system, dental surgical simulation, automatic skill evaluation.

1. INTRODUCTION

Many kinds of medical or dental surgical education systems have been proposed [Kne03], [DA04], [DD09], [Fra10]. In this paper, we construct a smart but cheaper dental surgical simulation system. Recently, an undergraduate dental student has few chances to experience practices dental surgical operations for patients. Therefore, the system is quite useful for student education.

As very few similar works, we focus on Kim's approach [LSM04], [HLM06a], [HLM06b]: volumetric implicit surface is used for surface modeling and haptic rendering while scraping. The main defective points are as follows: (1) A virtual tooth is roughly approximated, which is not a real patient data captured from a practical CT scanner. (2) Each bar and turbine are roughly expressed by combination of bigger ball and circle pillar. This approximation differs from real kinematic relationship between tooth, bar, turbine which are really used by a dental doctor in a hospital.

On these observations, we propose the other dental surgical simulation system. First of all, all teeth data are captured from real patients, and dental bar, turbine, miller are captured from real dental tools by a dental CT scanner in a hospital. Then, we convert patient tooth and dental bar into an octree (a set of cubes) and a set of points. Then, based on the hierarchical structure of octree representation in positioning, we can quickly check an intersection volume of an octree-based tooth and a point-based dental bar. Using the intersection volume, we simultaneously and precisely calculate force and moment artificially.

Our system is a mixed reality system which consists of visual, tactile, and sound realities. Therefore, we can learn a lot of realistic operation skills on demands. Moreover, our system has two wonderful characteristics as follows: (1) A doctor flexibly and directly selects physical parameters concerning to visual and tactile realities. Needless to say, the doctor has many practical experiments. For this reason, our system's realities are extremely improved. (2) This system automatically evaluates a student's skill by a numerical number between 0 and 100. The numerical point is calculated by comparing two teeth deformed by profession and beginner. Therefore, a student himself can learn several kinds of dental operation skills on-demand without the help of any professional person.

In this paper, we briefly explain our dental simulation system, models of patient teeth and dental tools in section 2. Especially in our system, a dental doctor uses dental bar and mirror cooperatively. For this reason, our system has two haptics (force feedback devices) PHANToM OMNI. In section 3, we explain how to improve visual reality, and then in section 4, we explain how the doctor selects a lot of parameters for cutting tooth. In section 5, we indicate evaluation functions for two typical operation tasks. Finally in section 6, we conclude this research.

2. SYSTEM STRUCTURE

In this section, we firstly describe the system architecture of our dental surgical simulation. Then, we explain dental turbine and mirror in our dental surgical system. In succession, we show models of patient teeth, dental bars, turbine, and mirror.

Architecture

The reality of our dental simulation comes from the following three aspects [NSK*08a], [NSK*08b]. One is a visual reality designed by the OpenGL. The OpenGL is the most popular API for computer graphics. Another is a sound reality which motor and drill sounds are directly memorized by a high-quality microphone. According to the speed of turbine, we can hear a mixture of rotating motor and drilling tooth, which is controlled by the OpenAL. The other is a tactile reality made from the OpenHaptics. The OpenHaptics, especially, HDAPI (Haptic Device API) is the API for controlling completely a force feedback device PHANToM provided by SensAble Technologies Inc. Our basic software roughly consists of three procedures such as calculating collision check, doing interference volume, and generating force sequence [NK10]. Each force is always felt by the force feedback device PHANToM OMNI based on the OpenHaptics (HDAPI).

Finally, all are combined by Microsoft Foundation Class (MFC) as a human interface (Figures 1 and 2). In our dental simulation system, in order to save production cost, we use a popular PC with normal graphics card, the cheaper haptic (force-feedback) device. This is quite important for constructing an educational system.

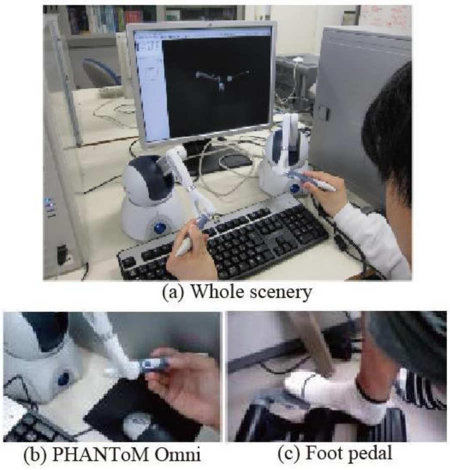

Figure 1. Panorama of dental simulation system.

Turbine and mirror in a dental hospital

In our system, we express all dental data without checking their intersection, for example, dental turbine and mirror by STL. If a dentist treats a molar tooth, he should checks its part by using the dental mirror because he cannot observe the inner part straightforwardly.

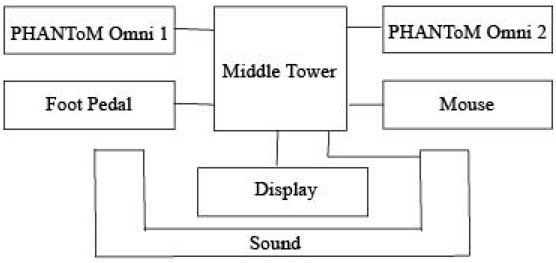

Figure 2. Architecture of dental simulation system.

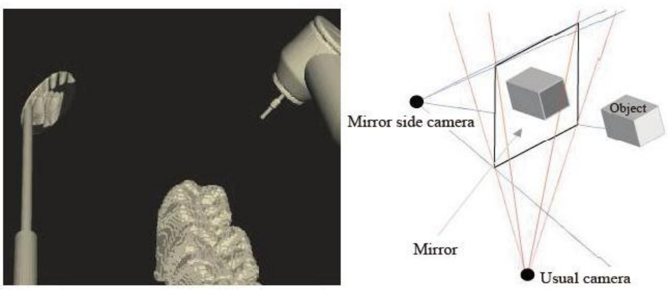

Figure 3. Cooperative treatment of dental mirror and bar.

Then, a dentist removes a decayed tooth by a dental bar. This is achieved by two force feedback devises of dental bar and mirror. By using these tools, the dentist can act similar surgical treatments (Fig.3). For mounting this dental mirror, we use the technique of off screen rendering. The technique is as follows: the picture seen from the other side of the dental mirror is the same as the picture that is reflected in the front of the mirror. Therefore, the camera image seen back of the mirror is described in the dental mirror.

Various models

2.3.1 Model of tooth, turbine, and bar

In order to capture real shapes of tooth, bar, and turbine in a dental hospital, we use a computed tomography (CT) scan (Figures 4 and 5). It uses X-rays so as to make detailed pictures of structures in and around a human oral. Therefore, we can exactly and individually capture teeth, maxilla, mandible bone, lips, and muscles as several kinds of data structures including STL format. The STL format is one of standard formats for the exchange of surface shape data, especially in rapid prototyping field, which replaces the original surface with a collection of triangulated surface segments. In our system, we precisely use triangular polyhedrons (STL) with the highest resolution 100% from the popular CT scanner with high precision.

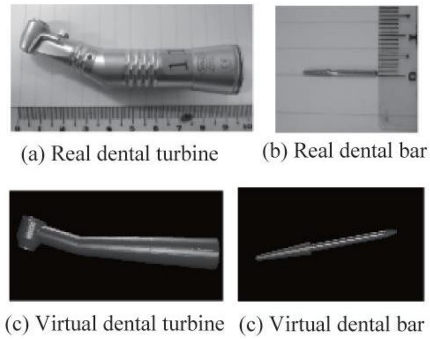

Figure 4. (a) Real dental turbine, (b) real dental bar, (c) virtual dental turbine, (d) virtual dental bar.

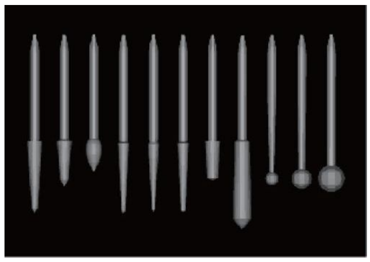

Figure 5. Many kinds of STL-based bars.

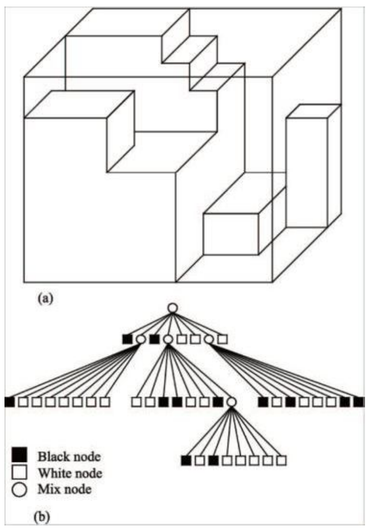

Figure 6. An octree representing a 3-D environment with objects. It has the hierarchical structure in positioning.

2.3.2 Octree-based tooth model

In this system, actual STL forms of patient teeth and also dental bars are converted into octree-based teeth and point-based bar, respectively (Fig.6) [JT80]. Based on the hierarchical structure in positioning, the intersection between octree-based tooth and point-based bar can be calculated with high-speed. First of all, we describe a classic method converting the STL format into the octree as follows: If a cube of an octree is inside some convex STL polyhedron, the cube is represented as a black node in the octree. If a cube of an octree is outside all convex STL polyhedrons, the cube is represented as a white node in the octree. Otherwise, the cube is represented as a mix node. Moreover, this procedure is recursively continued for only mix nodes until the octree level corresponds to a given maximum level. The mix node is converted to the black node if the octree level corresponds to the maximum one (Fig. 6).

This classic method is quite time consuming because a 3-D concave STL tooth should be converted into a set of 3-D convex STL parts. To overcome this defective problem, we propose a new method using GPU (Graphics Processing Unit). In general, the STL format can be efficiently converted into octree at high speed by using GPU (Graphics Processing Unit) (Figures 7 and 8). The GPU's Z buffer and parallel schemes quickly convert the STL polyhedral model into a set of 3-D hexahedra as a raster scanner, and then the hexahedron set is easily converted into the octree (Fig.9).

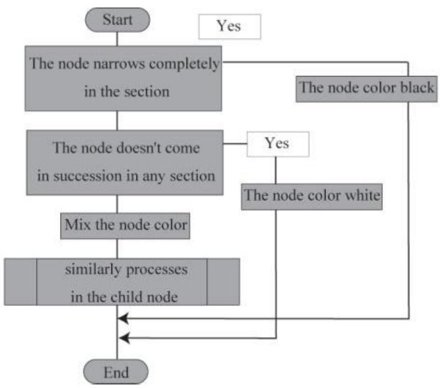

Figure 7: Conversion from many perpendiculars of an object to an octree.

We show row data of STL teeth before conversion, and numbers of octree nodes, their memory storage (Bytes) after conversion in Tables 1, 2 and 3, respectively. Here, as a pre-processing in our system, we indicate conversion time from STL-based teeth to octree-based teeth by GPU (Fig.10). Here the accuracy is 20μm in case of the octree with level 9, the accuracy is 10μm in case of the octree with level 10. As shown in Fig.10, we understand that the computation complexity (processing time) directly depends on not the number of STL patches but the octree level. As a result, we usually use the most precise 100% STL teeth in our research.

As contrasted with this, each dental bar is firstly converted from STL form into an octree, and then is converted from the octree into a set of points which are vertices of octree cubes (Fig.11). Furthermore, we note that those of dental bar are relatively small enough. Therefore, all are completely stored in the main memory in a personal PC.

Teeth	Patch number	Vertex number
6% STL	8,996	26,988
12% STL	18,016	54,048
25% STL	36,036	108,108
50% STL	72,096	216,288
100% STL	144,216	432,648

Table 1. Numbers of patches and vertices of row STL tooth.

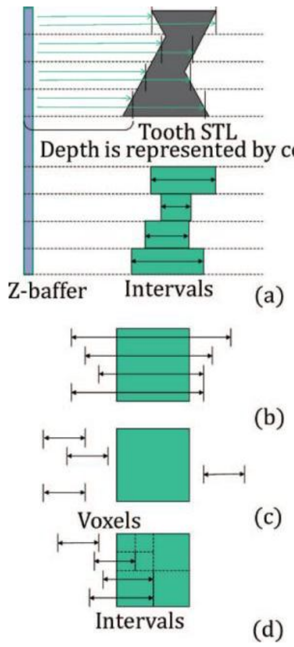

Figure 8. Conversion from a concave STL polyhedron to an octree via many digital intervals by GPU. (a) Depth calculation and interval collection of STL by GPU. (b) If a cube is to be inside its intersecting intervals, we give a black node for the cube. (c) If a cube is to be outside its intersecting intervals, we give a while node for the cube. (d) Otherwise, we give a mix node for the cube.

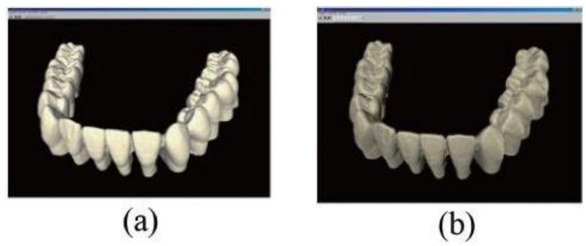

Figure 9. (a) STL-based teeth before conversion. (b) Octree-based teeth after conversion.

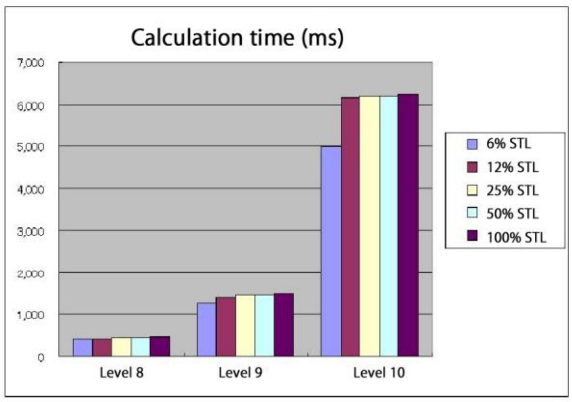

Figure 10. Conversion time from STL-based teeth to octree-based teeth by GPU.

2.3.3 Multi-layers structure

Each tooth has the multi-layers structure of enamel, dentin, dental pulp, and dental caries [GH91]. In order to improve the visual reality, a dental doctor easily chooses these colors. In addition, the doctor can select those spring, damper, friction, hardness coefficients so as to improve the tactile reality. The force magnitude and direction depend on an intersection set between point-based bar and octree-based tooth, and substantially depends on the speed before collision (Figures 11 and 12).

Level	8	9	10
6% STL	135,649	549,209	2206,913
12% STL	136,425	553,369	2214,377
25% STL	136,377	552,633	2212,721
50% STL	136,385	552,049	2214,505
100% STL	136,441	552,489	2213,633

Table 2. Numbers of nodes in the octrees after conversion.

Level	8	9	10
6% STL	4,595,712	19,292,160	77,508,608
12% STL	4,624,384	19,378,176	77,545,472
25% STL	4,624,384	19,349,504	77,492,224
50% STL	4,624,384	19,333,120	77,549,568
100% STL	4,624,384	19,349,504	77,520,896

Table 3. Memory storage of the octrees after conversion (Bytes).

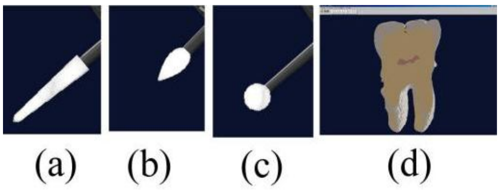

Figure 11: (a),(b),(c) Many kinds of point-based bars. (d) Tooth model of Multi-layers structure.

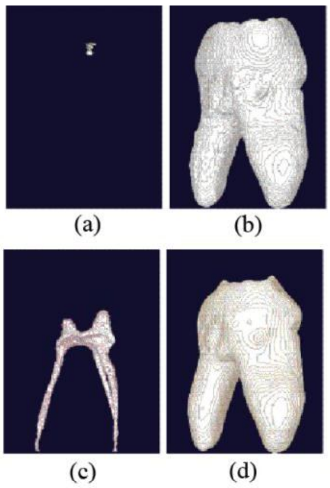

Figure 12: (a) Octree-based decayed tooth, (b) enamel material, (c) ivory material, (d) dental pulp in a back tooth (molar).

3. IMPROVEMENT OF VISUAL REALITY

In the research, a high-speed collision-check algorithm selects the intersection between octree-based tooth and point-based bar. The octree-based tooth consists of many cubes, and therefore their visibility is bad. To overcome this problem, we firstly used the traditional marching cubes algorithm [LC87]. However, since the visible reality is still not good, we modify the traditional algorithm as follows. In the classic marching cubes algorithm, the normal vector is determined by considering the XYZ direction neighborhood $2^3 = 8$ voxels of an arbitrary voxel. Therefore, in order to improve the reality of visibility, the normal vector is determined by considering the neighborhood $4^3 = 64$ voxels, and also the normal vector is determined by considering $6^3 = 216$ voxels (Fig.13).

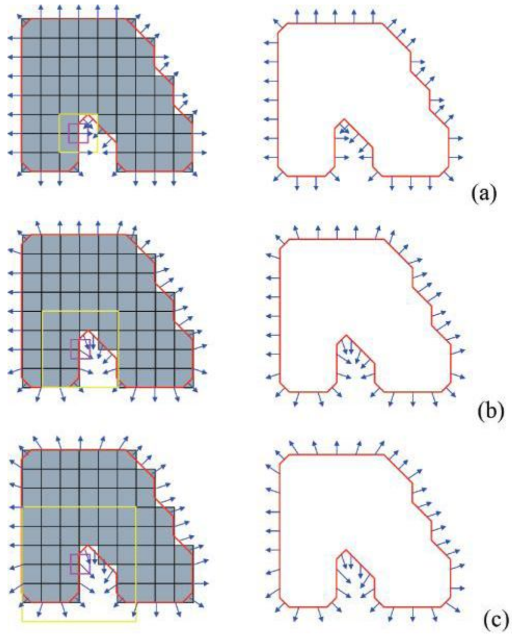

Figure 13. (a),(b),(c) Normal vector normalization by averaging $2^3 = 8$, $4^3 = 64$, $6^3 = 216$ neighbors in our modified marching cubes method.

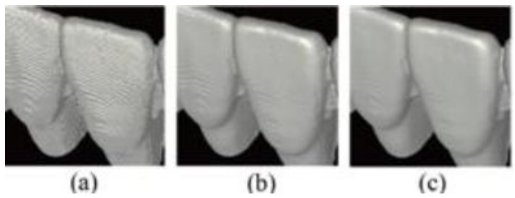

Figure 14. (a),(b),(c) Three images of octree-based teeth by the modified marching cubes method under averaging $2^3 = 8$, $4^3 = 64$, $6^3 = 216$ neighbors.

As a result, the reality is quite improved (Fig.14), and also the calculation time is almost less than the video rate. However, the time is sometimes over depending on the operation (conversion of part of $1/32^3$ in whole space) as shown in Fig.15.

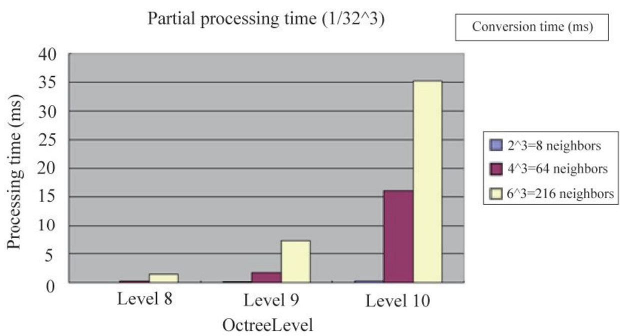

Figure 15. Calculation time of normal vector at each octree level by the modified marching cubes (Partial conversion of $1/32^3$ whole space).

4. PHYSICAL PARAMENTER SELECTION

In our software, a dentist can flexibly selects many physics parameters concerning to tactile and visual realities. For this purpose, we prepare a wonderful window used by the dentist (Fig.16). First of all, a doctor selects one of "enamel", "dentin", "dental pulp", "dental caries" files in order to choose its spring, damper, frictional coefficients, and hardness (how to drill a tooth easily). They are physics parameters for tactile feeling.

Here, the doctor can select the sense for cutting a tooth by (how much a tooth part is easily drilled) * (how much a dental bar drills easily) * (rotational speed of bar). In particular, the hardness is selected between 0 (not easy to drill) and 1 (easy to drill). We set enamel, dentin, dental pulp and dental caries as 0.1, 0.1, 1.0, 0.5, respectively, as the initial values (Fig.16).

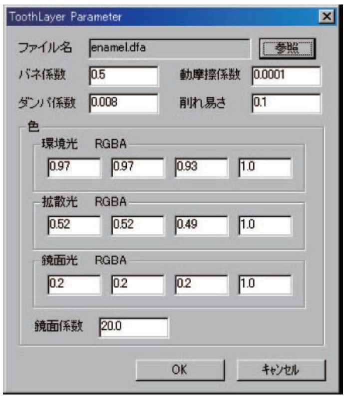

Figure 16. A window for determining several physical parameters concerning to visual and tactile realities.

On the other hand, the doctor selects a drill cutting ability between 0 (not easy to drill) and 1 (easy to drill). Finally, rotational speed of dental bar can be controlled between 0: 0rpm - 1: about 40000rpm by stepping or releasing the foot pedal.

Moreover, concerning to physics parameters of visual reality, the dentist himself straightforwardly selects RGBA values according to his real experiences. R is red, G is green, and B is blue of three primary colors. The A means the transparency. In addition, he chooses "ambient: the light that came from all directions at a time", "diffuse: reflect in all directions because of the coming light", "specular: light that formed a bright, white spot to the reflection side".

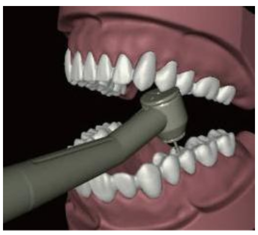

Figure 17.Cavity preparation.

Figure 18. Automatic evaluation system.

5. STUDENT OPERATION EVALUATION

This system automatically evaluates student's skills in dental surgical operation (Figures 17 and 18). Concerning to this, we explain how to evaluate student operation in two typical dental tasks as follows (Full marks are 100 point).

(a) Caries removal task (Evaluation whether the caries was smoothly removed or not) (Figures 19 and 20)

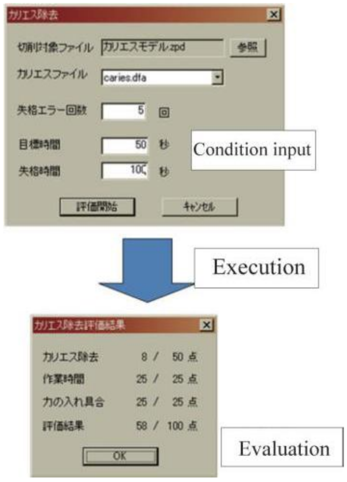

Figure 19. Caries removing task.

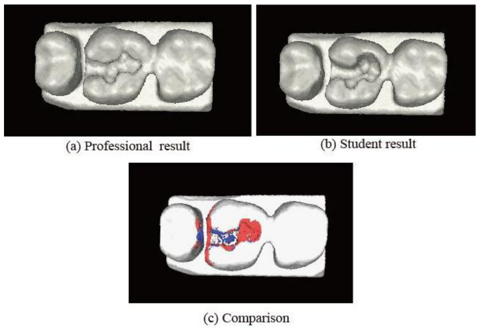

Figure 20. (a) Professional result, (b) Student result, and (c) over and under cutting regions are colored by red and blue, respectively, for caries removing task.

Measurement contents are as follows: Numbers of two kinds of force errors, initial and final caries volumes, start, final, target, and failure time. This detail is described in Table 4.

No.	Item name	Detail
1	Score of removing caries	= (Final caries volume) / (Initial caries volume)*50. Full marks are 50 points. It is expressed by the decimal point.
2	Score of executing time	= (failure time - (finish time-start time)) / (failure time- target time) * 25. Full marks are 25 points. Less than 0 is expressed as 0 point, and more than 25 is represented as 25 points. All are represented by the decimal point.
3	Score of controlling forces	= (The number of forces more than a given threshold – the number of relatively larger forces) / (The number of forces more than a given threshold) * 25. Full marks are 25 points. Less than 0 is expressed as 0 point, and more than 25 is represented as 25 points. All are represented by the decimal point.
4	Total score	= Score of removing caries (50 points) + Score of executing time (25 points) + Score of controlling forces (25 points). Full marks are 100 points.

Table 4. Evaluating terms for caries removing task.

(b) Cavity preparation task (Evaluation whether the ideal cavity was built or not) (Fig.21)

Measurement contents are as follows: Under and over cutting volumes, number of force errors, start, final, and target time. This detail is described in Table 5.

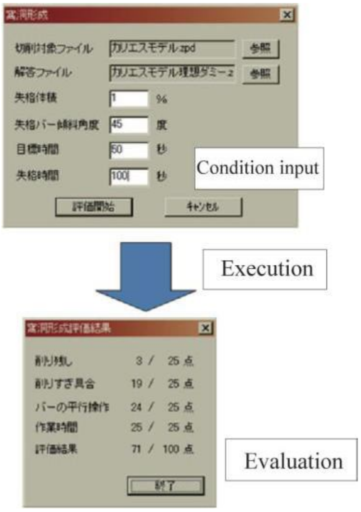

Figure 21. Parameter setting and operation evaluating for the cavity deforming task.

6. SUMMARY

In this paper, we explained our dental surgical simulation system for educational purpose. Especially, we illustrate how to obtain visual and tactile realities, and also show automatic evaluation of student surgical skills. We ascertained that our system is superior to previous similar ones concerning to these activities. This is achieved as follows: (1) our system was compared with other commercial or non-commercial surgical systems in several workshop demonstrations. (2) our system is carefully testing and investigating by over 100 professors and students in the faculty of dentistry.

For the education purpose, we frequently heard that ten cheaper systems (For example, one million Japanese yen) are better than one expensive system (For example, 10 million Japanese yen). Because the system consists of commercial-based PC and graphics acceleration board, and the cheapest haptic device, the cost is less than fifty hundred thousand yen.

Furthermore, we use open source software in visual, tactile, and sound realities as OpenGL, OpenHaptics, and OpenAL, respectively. Therefore, our dental surgical simulation system has high extendibility. As a result, our system has a wonderful potential for education purpose.

No.	Item name	Detail
1	Score of under cutting the ideal cavity	= Under cutting volume * demerit mark coefficient * 100 / cutting volume proposed by profession. Under cutting volume is digitally calculated as (final volume **AND** (**NOT** ideal cavity volume by profession)). Full marks are 25 points.
2	Score of over cutting the ideal cavity	= Over cutting volume * demerit mark coefficient * 100 / cutting volume proposed by profession. Over cutting volume is digitally calculated as ((**NOT** final volume) **AND** ideal cavity volume). Full marks are 25 points.
3	Score of parallel operation of bar	If a dental doctor operates a dental bar in parallel, its operation force constantly decreases. For this reason, we indirectly evaluate the number of parallel operations by the number of relatively larger forces. As the larger the number of relatively larger forces* force error coefficient, the larger the score is. A threshold of force error is given in advance such as 3.0 N. Full marks are 25 points. All are represented by the decimal point.
4	Score of executing time	= (executing time - target time) * executing coefficient / 60. Executing time = final time-start time. 60 means the translation parameter from seconds to minutes. Full marks are 25 points. All are represented by the decimal point.
5	Total score	= Score of under cutting the ideal cavity (25 points) + Score of over cutting the ideal cavity (25 points) + Score of parallel operation of bar (25 points) + Score of executing time (25 points). Full marks are 100 points.

Table 5. Evaluating terms for cavity deforming task.

7. ACKNOWLEDGMENTS

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