Computer-Aided Design of Functional Occlusal Surface for Dental 3-D CAD system

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Graduate School of Science and Technology
Niigata University

Tomoaki MARUYAMA

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1. Introduction

1.1 Purpose of dental CAD/CAM systems

Dental prostheses such as crowns, bridges and complete dentures are used to restore patients' dentitions lost with dental caries and periodontal diseases. They are usually manufactured by using conventional casting technique [1-4]. Since their design and manufacture require sophisticated skills, their production quality cannot easily be maintained within acceptable range in clinic. Then, attempts have been made to apply advanced CAD/CAM (Computer-Aided Design / Computer-Aided Manufacturing) technology for industrial use into this dental field [5-20]. The main purposes of dental CAD/CAM system are as follows [5,6]: 1) to produce dental prostheses with high strength and uniform quality by using material blocks such as alumina- and zirconia-baced ceramics; 2) to standardize their design and manufacture processing; and 3) to reduce production time and cost. CAD/CAM systems enable us to use high-strength and aesthetic materials such as alumina- and zirconia-based ceramics for the first time, extending lifetime of dental prostheses. Additionally, computer-aided automatic fabrication of dental prostheses enables us not only to simplify its entire process, but also to restore patients' dentitions within a day. Since such advanced technology and production concepts have already been accepted widely in dental science, many different kinds of dental CAD/CAM system are commercially available at present [5,6]. They can be considered an indispensable manufacturing tool for dental restorations.

The main difference between industrial- and dental-CAD/CAMs lies in the number of products. The former produces a large number of ready-made products, while the latter produces custom products. In order to manufacture dental prostheses for individual patients, dental

CAD/CAM systems have to consist of three elements [5,6,21]: 1) digitizing of patients' dentitions; 2) computer-based design; 3) milling and grinding of dental prostheses from a material block according to CAD planning. Firstly dentists have to digitize patients' dentitions such as abutment, neighboring and opposing teeth intraorally or extraorally by means of accurate 3D digitizer such as laser scanner. Secondly a prosthesis is designed by means of a 3-D design software in an attempt to satisfy several required conditions. Finally the prosthesis is manufactured by means of a computer-control milling machine. Such advanced CAD/CAM technology achieved WYSIWYG (What You See Is What You Get) even in custom production of dental prostheses.

1.2 Review of dental CAD/CAM systems

First idea for applying industrial CAD/CAM into automatic fabrication of dental prostheses was proposed by F. Duret in 1971 [22]. At that time, industrial manufacturing had been shifted drastically from handicraft production to computer-controlled machine production. The automatic manufacturing enabled us to pump higher-quality products and to reduce production cost. Duret's attempts of CAD/CAM application to dentistry, however, has not been succeeded, because computer abilities were insufficient at that time and dental prostheses are custom products as mentioned in the previous section. After a long-time accumulation of enthusiastic basic studies since the 1970s [23-26], E.D. Rekow and F. Duret proposed a practical dental CAD system for the automatic design of crowns independently [27-31], followed by CEREC system (Sirona, Bensheim, Germany) in 1986 [32-36]. The first clinical application of dental CAD/CAM was achieved by CEREC 1 system [5,6,32,33], which was applied to fabricate eight inlays. Subsequently, clinically available dental CAD/CAM systems have been developed one after another, such as DentiCAD

(Bego Medical, Bremen, Germany) with artificial intelligence technology by Rekow in 1987 [27], Duret system (Hennson International, France) by Duret in 1988 [22], Procera (Nobel Biocare, Göteburg, Sweden) [37,38] and GN-1 (GC International, Tokyo, Japan) [39-40].

Currently, many different dental CAD systems applicable in clinic are commercially available (Table 1,2) [5,6]. One of the most popular dental CAD/CAM systems is CEREC 3D (Sirona), which is a successor of CEREC 1 system [5,6,33]. Its features are as follows: 1) an intraoral scanning of dentitions; 2) an automatic virtual occlusal adjustment with a 3-D visualization; and 3) fabrication of ceramic restorations within a single clinical appointment. This system has an intraoral 3-D digitizing device for scanning patients' dentitions such as abutment, neighboring and opposing teeth, while other systems usually employ an extraoral digitizing of a plaster model of patients' dentitions by using a mechanical or optical measuring device. The digitized data is automatically fed into a 3-D designing software for dental CAD, enabling dentists to immediately design dental prostheses in clinic. This CAD software with a 3-D visualization achieved an intuitive and easy design of dental prostheses including complicated occlusal-surface restoration. The design data is automatically transferred into a grinding machine capable of fabricating a prosthesis with two different types of cylindrical diamond taper bur. The entire CAM process is completed merely in a few minutes. Then, it takes about an hour to accomplish the entire process of the chair-side design and fabrication by CEREC 3D.

1.3 Outline of thesis

Presently, CAD/CAM systems are known to be useful even for designing functional occlusal surfaces [41-46], which have to be designed very carefully, considering their function in the intercuspal position, chewing and tooth sensation. Occlusal surface consists of cusps and fissures, which are usually designed anatomically in dental prostheses. It is of specific importance that each cusp of the tooth has to contact with the opposing teeth at several points in the intercuspal position in order to stabilize the tooth during biting. Thus, determination of occlusal contact points on the occlusal surface is very crucial in the prosthetic design [1-3]. CAD-based design of the contact points, however, has been done on a trial-and-error basis in order to avoid occlusal interference during tooth excursions. To assist such time-consuming design process, present dental CAD systems usually have a certain function capable of checking occlusal interferences using patients' functional impressions recorded during tooth excursions [5,6]. In order to avoid such groundless design of occlusal contact points, we have to establish a more grounded and subjective design procedure. It should be noted that we can compute whether the designed contact points interfere with the opposing cusps or not, if data of the opposing-surface geometry and tooth excursions are both given in three dimensions. Then, if tooth excursions can be simulated using a virtual dental articulator in dental CAD system, we can compute the opposing surface regions in which the contact points without cuspal interference during excursions are located. Visualization of such regions helps us to easily determine the contact points of the prosthesis. In order to realize such trial-and-error-free assist, this study proposed a virtual semi-adjustable articulator, which can be implemented in dental CAD, and a method for computing and visualizing opposing surface regions suitable for contact points to be located.

This thesis consists of five different chapters as shown in Fig. 1. To introduce my trial dental CAD system, Vocs-2, chapter 2 outlines its basic components such as tooth model and design tools. Chapter 3 describes a simulation of tooth excursions by a virtual articulator in dental 3-D CAD system, and an automatic adjustment method of the articulator using functional impressions. Chapter 4 is the dominant part of this thesis, proposing a new subsystem enabling us to assist for designing occlusal contact points. Finally, chapter 5 summarizes outcomes of this study.

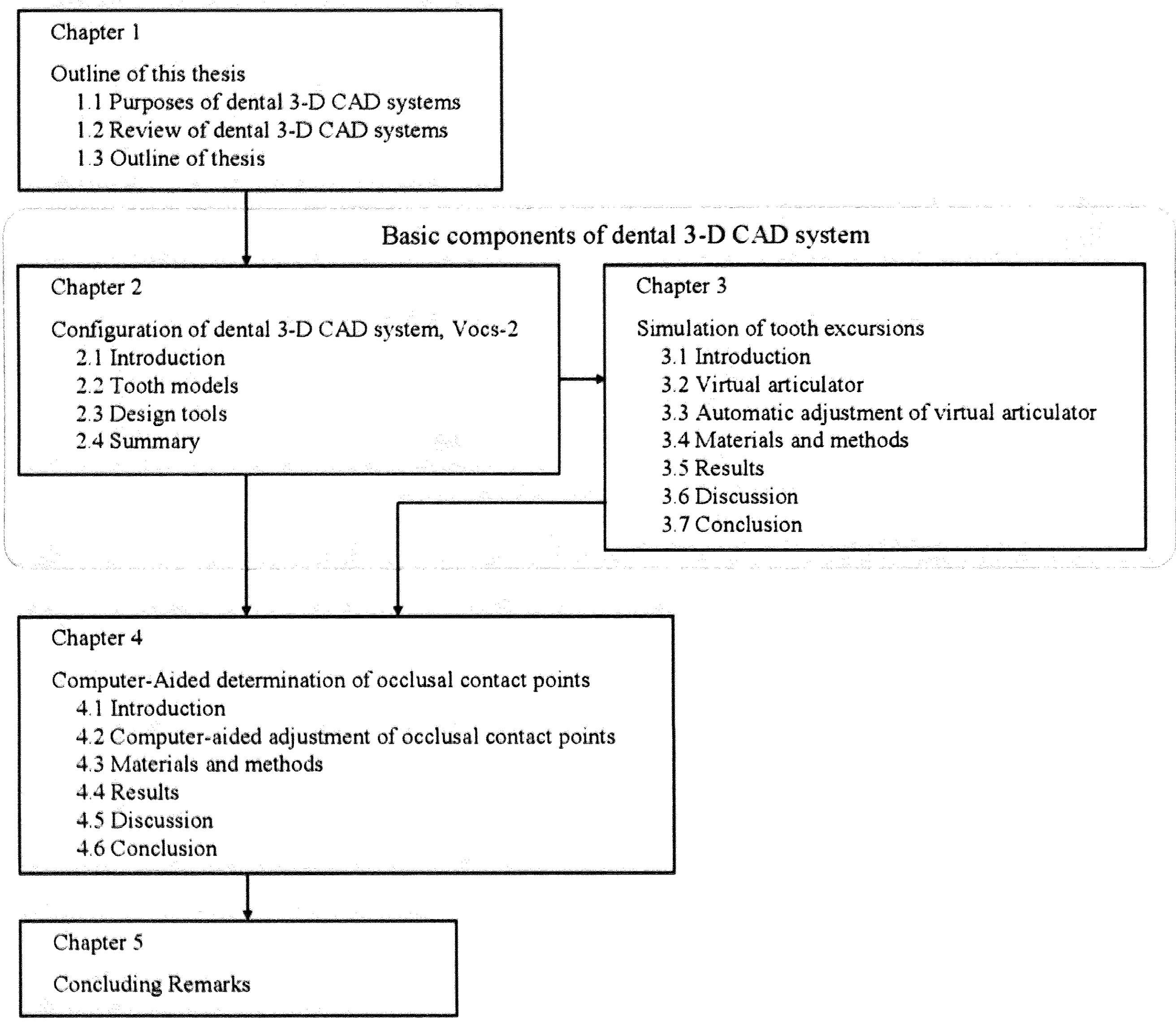


Figure 1 Outline of this thesis.

Table 1 Overview of dental CAD/CAM systems.

CAD/CAM systems	Restoration					Material				
	Veneer	Inlay / Onlay	Crown	Bridge	Occlusal Surface	Ceramic-Alumina	Ceramic-Zirconia	Other Ceramics	Titanium	Composite
CEREC 3D Sirona, Bensheim, Germany	○	○	○		○		○	○		○
CEREC InLab Sirona, Bensheim, Germany	○	○	○	○	○	○	○	○		○
Cercon Degudent, Frankfurt, Germany			○	○			○			
Cadim Advance, Tokyo, Japan	○	○	○	○	○	○	○	○	○	○
DECIM Cad.esthetics AB, Skellefteá, Sweden		○	○	○	○		○			
Decsy Media, Tokyo, Japan	○	○	○		○	○	○	○	○	○
etkon etkon AG, Gräfelfingen, Germany			○	○		○	○		○	○
Everest KAVO, Leutkirch, Germany	○	○	○	○	○	○	○	○	○	○
GN-1 GC International, Tokyo, Japan			○	○	○	○	○	○	○	○
DigiDent Hint-ELs, Griesheim, Germany			○	○	○	○		○	○	○
Precident DCS DCS AG, Allschwil, Switzerland			○	○		○	○	○	○	○
Lava 3M ESPE, Seefeld, Germany			○	○			○			
Procera Nobel Biocare, Göteburg, Sweden	○		○	○		○	○		○	
Pro 50 Cynovad, Saint-Laurent, Canada	○	○	○	○	○	○	○	○	○	○
Wol-Ceram Wol-Dent, Ludwigshafen, Germany			○	○		○				

Table 2 Comparison between several dental CAD/CAM systems in tooth digitization and occlusal adjustment.

CAD/CAM systems	Tooth digitization	Occlusal adjustment
CEREC 3D Sirona, Bensheim, Germany	Optical 3-D digitizing (Intraoral)	Functional impression-based adjustment
Cadim Advance, Tokyo, Japan	Mechanical 3-D digitizing (Extraoral)	-
Decsy Media, Tokyo, Japan	Optical 3-D digitizing (Extraoral)	Functional impression-based adjustment
GN-1 GC International, Tokyo, Japan	Optical 3-D digitizing (Extraoral)	Functional impression-based adjustment
Procera Nobel Biocare, Göteburg, Sweden	Optical 3-D digitizing (Extraoral)	-

2. Configuration of dental 3-D CAD system, Vocs-2

2.1 Introduction

In order to establish an assisting technology for designing of occlusal contact points, a trial dental 3-D CAD system, "Vocs-2", have been developed (Fig. 2) [47-54]. The system consists of several subsystems with inherent functions as follows: 1) metamorphosis with wax-up-like operationality [47-49]; 2) semi-automatic implantation of a data-base crown model to abutment tooth [49,50]; 3) semi-automatic adjustment of contact to neighbouring tooth [50]; 4) adjustment of entire occlusal surface of the crown [51-53]; 5) positional shift of tooth cusps [51]; 6) metamorphosis for creating occlusal contact point of the crown [52]; and 7) automatic eliminator of occlusal interference [51].

This chapter describes essential components such as a tooth model and design tools in Vocs-2 system. Section 2.2 describes a tooth model with both surface- and solid-descriptions. The tooth model consists of a solid description of the occlusal surface and a surface description of the entire crown. The use of a solid model enables us to easily detect the contact and interference of the opposing teeth. In order to make the two different models agree with each other in corresponding portions, this study introduced a mutual transform between them, which is always determined uniquely if one of the models is deformed infinitesimally. Section 2.3 describes a partial metamorphosis operator, to which Hit-or-Miss transform developed in the field of mathematical morphology was applied. The partial deformation operator is able to partially dilate or erode the contour around the deformation center, without loss of smoothness, by adjusting only two parameter values representing the amount and extension of the deformation. Large deformation is always accomplished by repeating a minute deformation, thus maintaining the agreement of the two models. Finally section 2.4 summarizes this chapter.

2.2 Tooth models

In Vocs-2 system, the tooth model comprises a set of two different models as follows: 1) a complete surface model of the contours of the tooth, denoted as S (Fig. 3-a); and 2) a solid model of the occlusal surface, denoted as V (Fig. 3-b), and bilateral transformations between them, as shown in Fig. 4. Solid model V is effective for adjusting the contours of the occlusal surface, such as elimination of interferences between opposing surfaces, while surface patch-based model S is suitable for describing complicated curved surfaces using a small number of parameters. Tooth models S and V were created in the following manner: 1) to digitize a plaster tooth model four times larger than life size; 2) to create a complete surface model of the tooth contours, consisting of eight Bezier surfaces; and 3) to create a solid model of the occlusal surface from the surface model.

If the models are transformed independently, inconsistencies between model S and model V can occur. To avoid such inconsistency, transformations between models S and V capable of maintaining their consistency were defined in a strict manner. The transformation from surface model S into solid model V and its inverse transformation are denoted as T and T^{-1}, respectively. Transformation T: $S \rightarrow V$ was defined as that directly transforming S into V by using one-to-one correspondence. Its inverse transformation T^{-1}: $V \rightarrow S$, on the other hand, cannot be determined uniquely as well as cannot satisfy the consistency between S and V. To eliminate these restrictions, transformation T^{-1} was defined as a combination of two different transformations as follows: 1) to calculate a least-square approximation of surface model S, denoted as S', from transformed solid model V; and 2) to apply transform T to S' in order to obtain solid model $V'=T(S')$. The consistency between V' and S' always maintains, but V' does not necessarily coincide with V.

2.3 Design tools

Hit-or-miss transformation developed in the field of mathematical morphology [55,56] was applied into metamorphosis of solid model V. All metamorphosis operations used in Vocs-2 are materialized as an iteration of a simple morphological operation, referred to as "dilation". The most fundamental operator in Vocs-2 is referred to as a "local dilation", which is defined as a weighted dilation capable of swelling a portion of the model surface without loss of smoothness. The extent of this deformation can be adjusted by using a single parameter, referred to as the "window parameter". Any large metamorphosis operation was materialized as the iteration of this weighted dilation, in an attempt to avoid any inconsistency between S and V. Such morphological operations are very similar to a conventional wax-up method, in which the crown contour is formed by heaping up wax little by little. Metamorphosis of surface model S, on the other hand, was realized as a sequence of three operations: 1) to calculate surface points from data of Bezier control points; 2) to shift surface points (metamorphosis); and 3) to estimate the Bezier control points from the shifted surface points in the sense of least squares. Thus, this study did not employ a conventional metamorphosis operation of directly shifting Bezier control points, because the operator cannot easily forecast the outcome correctly before metamorphosis.

Vocs-2 includes several design tools as follows: 1) to fit the margin line of the crown to that of the abutment tooth; 2) to semi-automatically create a contact point between proximal surfaces; 3) to manually adjust the position and orientation of the entire occlusal surface; 4) to shift the tooth-cusp position semi-automatically; and 5) to create occlusal contact points semi-automatically.

2.4 Summary

Vocs-2 system has two distinct features of a tooth model with both surface- and solid-descriptions and a partial metamorphosis operator, while conventional dental CAD systems employ only a tooth model with surface description. These features achieved a detailed design of crown's occlusal surfaces with natural and functional contour, without loss of operationality. The solid model enables us to easily compute the inter-surface distance and interference between opposing occlusal surfaces. Such merits are advantageous particularly in a real-time visualization of the inter-surface distance map and an automatic elimination of cusp interference.

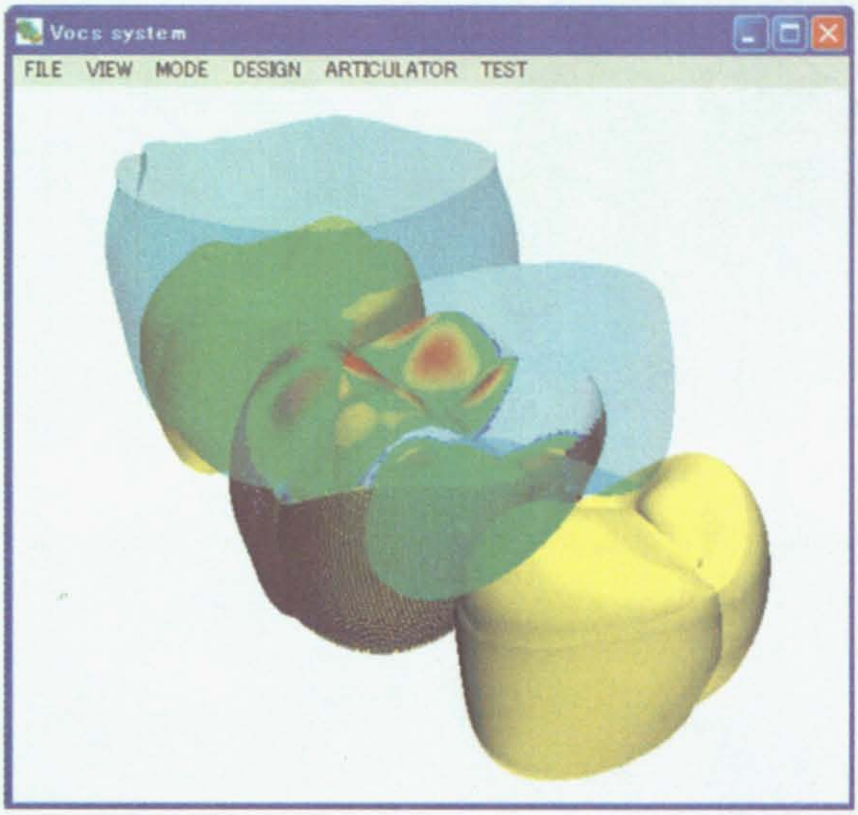


Figure 2 Dental 3-D CAD system, Vocs-2 (Visualization of inter-surface relationship).

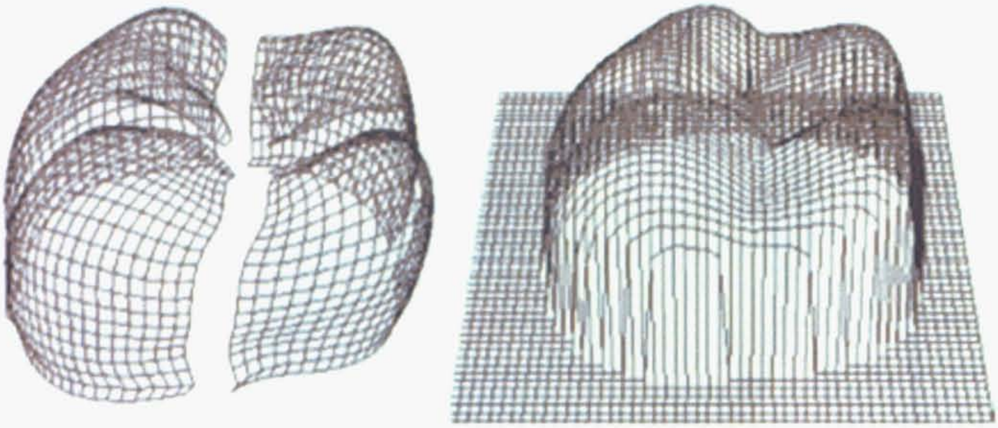


Figure 3 Surface and solid models of tooth crown used in Vocs-2. (a) Surface model, (b) Solid model.

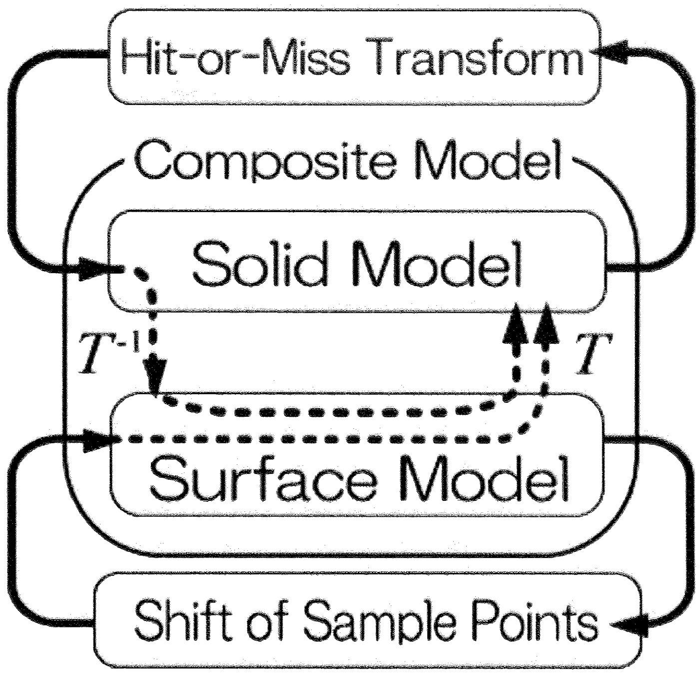


Figure 4 Composite tooth model integrating solid and surface models, and metamorphosis operation procedures.

3. Simulation of tooth excursions

3.1 Introduction

In order to design functional occlusal surfaces, dental CAD systems have to simulate not only the intercuspation, but also tooth articulation during excursions [1-3,57-62]. During tooth excursions, opposing occlusal surfaces separate or make contact with each other. Their separation is referred to as the "disclusion" in dentistry [1,3]. When designing a patients' crown, dentists have to provide its occlusal surface with suitable contacts both in the intercuspation and during tooth excursions. Presently available dental CAD systems usually use patients' functional occlusal impressions for the determination of interference-free contact points [5,6]. This clinical procedure, however, has been performed on a trial-and-error basis primarily by using visual inspection.

To improve such time-consuming procedure into a semi-automatic one based on quantitative evaluations, this chapter proposed two difference functions such as 1) a simulation of a dental articulator, which is a mechanical instrument capable of providing the patients' dental cast with various tooth-gliding movements, and 2) proximity mapping on the crown surface relative to its opposing occlusal surface. The articulator has several adjustable components as follows: 1) sagittal inclination of the condylar housing, and 2) sagittal and lateral inclinations of the incisal table. These variables are automatically determined in accordance with patients' functional occlusal impressions, employing an advanced 3D-registration-based technique. The entire procedure for adjusting a virtual dental articulator is summarized as follows: 1) to record patients' functional occlusal impression; 2) to compute articulator parameter values in order to make the recorded impression surface agree with that obtained from simulation of tooth articulation; and 3) to adjust the virtual articulator.

The next section describes a virtual articulator capable of simulating patients' tooth excursions. Then, Section 3.3 describes an automatic adjustment of the articulator using patients' functional occlusal impressions. In an attempt to verify its clinical applicability, experiments were carried out using Vocs-2 CAD system described in section 3.4, followed by section 3.5 presenting empirical results. Section 3.6 discusses the necessity of tooth articulation simulation in dental 3-D CAD, and compares occlusal adjustment using conventional CAD systems with that using the proposed virtual articulator. Finally, section 3.7 summarizes this chapter.

3.2 Virtual articulator

Dental articulators are classified three categories [1-3]: 1) fully adjustable; 2) semi-adjustable; and 3) non-adjustable. For computer simulation of tooth excursions, this study employed an arcon type semi-adjustable articulator, because of its relatively high reproduction accuracy of patients' tooth excursions and simple operation, as illustrated in Fig. 5. The virtual articulator consists of a maxillary frame and a mandibular frame, as usual. The mandibular frame has an incisal table guiding the tip of the maxillary incisal pole (IP), and condylar points (C_L, C_R) simulating the center of the condylar ball capable of moving along the maxillary condylar housing. Adjustable components of the articulator are as follows: 1) sagittal inclination of the condylar housing denoted as C_s ; and 2) sagittal and lateral inclinations of the incisal table, denoted as I_s and I_l , respectively. The articulator can simulate tooth excursions by moving IP from the intercuspal position to an eccentric position, such as protrusive and lateral positions. The patients' maxillary cast can be mounted on the articulator in a standard manner, using the average position and orientation of the occlusal plane with respect to the articulator. If detailed information from a face-bow transfer is available, the cast can be mounted more precisely. Subsequently, the mandibular cast can be mounted relative to the maxillary counterpart using intercuspation data, such as an occlusal record.

3.3 Automatic adjustment of virtual articulator

3.3.1 Outline of adjustment method for virtual articulator

The virtual articulator of Vocs-2 system enables us to simulate occlusal conditions during tooth excursions. Then, teeth impression during tooth excursions is determined by geometry of teeth and a tooth excursion simulated by the virtual articulator. In order to optimize adjustable parameters C_s and I_s of the articulator in accordance with patients' tooth excursions, this study proposed an advanced 3D-registrasion-based method for automatically adjusting the articulator in accordance with a patients' functional occlusal impression. The adjusting process is summarized as follows: 1) to take a functional occlusal impression formed by a protrusive movement; 2) to compute the value of parameters C_s and I_s to make a simulated virtual impression agree with the actual occlusal impression; and 3) to adjust the virtual articulator.

3.3.2 Similarity evaluation of actual and virtual impressions

In order to evaluate similarity of actual and virtual impressions, evaluation parameters were defined representing "proximity" and "penetration". Firstly the proximity was defined as follows. Patients' functional occlusal impression is denoted as S_m. An impression of opposing teeth during tooth excursion by articulator simulation is denoted as $S_v(C_s, I_s)$. An arbitral point on the actual impression S_m is denoted as P_m. The minimum distance between point P_m and virtual impression $S_v(C_s, I_s)$ is defined as $D(P_m)$. Then, the proximity parameter was defined as follows:

$$s^+(\alpha) \equiv \{P_m \in S_m \mid 0 \leq D(P_m) \leq \alpha\}, \qquad (3.1)$$

where α is a threshold parameter for evaluating the proximity between the two impressions. Next the penetration was defined as follows. Penetration areas of S_m into which opposing S_v was penetrated were defined as follows:

$$R \equiv \{P_m \in S_m \mid D(P_m) < 0\} \subseteq S_m. \qquad (3.2)$$

Then, the penetration parameter was defined as follows:

$$s^-(\beta) \equiv \int_R (D(P_m) / \beta)^2 \, dP_m, \qquad (3.3)$$

where β is a normalization parameter. Using the proximity and penetration parameters, the evaluation function was defined as their difference:

$$J[\boldsymbol{T}, \boldsymbol{R} \mid C_s, I_s, \alpha, \beta] \equiv s^+(\alpha) - s^-(\beta), \qquad (3.4)$$

where $\boldsymbol{T}$ and $\boldsymbol{R}$ represent the position and orientation of $S_v(C_s, I_s)$, respectively. If two impressions S_m and $S_v(C_s, I_s)$ are completely coincided with each other, proximity $s^+(\alpha)$ becomes maximum, while penetration $s^-(\beta)$ becomes zero, thus evaluation function J being maximized.

In order to evaluate the agreement of virtual and actual impressions, they are superposed by an iterative algorithm using a combination of a simulated annealing (SA) and a genetic algorithm (GA) for avoiding to obtain locally optimal solutions (Fig.6) [63-65]. Figure 6 demonstrates the algorithm to obtain $\boldsymbol{T}$ and $\boldsymbol{R}$ maximizing J, which has local maximums in general. In an attempt to avoid such local maximums, the algorithm starts with a large value of annealing parameters α and β capable of smoothing J. Subsequently, by gradual decreasing the value of α and β, we can find an appropriate candidate for the optimum solution providing the global maximum of J. Then, if this annealing process is repeated several times, we can have several candidates. Finally by using a GA technique, we could select one of the optimum solutions, denoted as $\boldsymbol{T}'$ and $\boldsymbol{R}'$. The maximized value of J obtained by the afore-mentioned process is defined as the value of evaluation function $J[C_s, I_s]$ as follows:

$$J[C_s, I_s] \equiv J[\boldsymbol{T}', \boldsymbol{R}' | C_s, I_s, \alpha, \beta]. \qquad (3.5)$$

3.4 Materials and methods

Vocs-2 system was implemented in C-language on a personal computer (Microsoft Windows XP, Celeron 2.4GHz). Tooth excursions were simulated by using the virtual articulator included in Vocs-2 system. As empirical data of tooth shape, a crown model of the lower first molar and intercuspated dental-arch model were employed (Fig. 7), including the lower second premolar, the lower first molar (abutment), the lower second molar, the upper first molar and the upper second premolar (opposing teeth). The models were obtained by digitizing plaster models four times larger than life size. Experiments were carried out, according to the following procedure: 1) to create a functional occlusal impression using the opposing teeth models; 2) to adjust the virtual articulator from the impression by means of the proposed method; and 3) to evaluate the values of the articulator parameters. To optimize articulator parameters C_s and I_s for a patients' impression, a downhill-simplex method was employed with evaluation function $J[C_s, I_s]$ mentioned in the previous section. In order to evaluate adjustment accuracy of the articulator parameters, two different virtual impressions were prepared (Fig. 8). Firstly, virtual impression S_1 was created by moving forward the virtual articulator with $C_s = 38°$ and $I_s = 38°$ (Fig. 8-a), where the motion distance of IP was set at 4 mm. Secondly, virtual impression S_2 was created by adding Gaussian noise (SD=0.1mm) to impression S_1 (Fig. 8-c).

By using each impression of S_1 and S_2 for adjusting the articulator parameters, we have two different set of the articulator parameters, denoted as $\mathbf{C}_1=\{C_{s1}, I_{s1}\}$ and $\mathbf{C}_2=\{C_{s2}, I_{s2}\}$, respectively. Then, estimation errors of $\mathbf{C}_1$ and $\mathbf{C}_2$ were evaluated by comparing them with their correct values (C_s=38° and I_s=38°). In addition, actual protrusive movement and that simulated by the articulator with $\mathbf{C}_1$ and $\mathbf{C}_2$ were compared. For such comparison, three occlusal contact points (P_A, P_B, P_C) were created on the crown surface by using Vocs-2 system (Fig.9). Then, the distance from every contact point to the opposing surface was computed during a protrusive movement from the intercuspal position to a protrusive position with a moved distance of 1mm at IP.

3.5 Results

Adjustment results of articulator parameters C_s and I_s are as follows. Figure 4 shows two-dimensional pseudo-color visualization of function $J[C_s, I_s]$ with its vertical and transversal axes of C_s and I_s, respectively. Color bar in Fig. 10 represents correspondence between color and the value of J. Figure 10-a shows adjustment results of the parameters obtained by using S_1. Estimated values of the articulator parameters were C_s=38.00° and I_s=38.00°, completely agreed with their correct values. Figure 10-b shows results of the articulator parameters obtained by using S_2. Estimated values were C_s=38.65° and I_s=38.18° including error component ΔC_s=0.65° and ΔI_s=0.18°, respectively. As shown in Fig. 10, no local maximum was observed near the solution in the distribution of J.

Empirical results of d_{min} during two protrusive movements at every contact points (P_A, P_B, P_C) are as follows (Fig. 11). The differences in separation between two simulated protrusions were negligible at all contact points, if the moved distance of incisal point IP lay within 1mm.

3.6 Discussion

Empirical results are summarized as follows: 1) in case of S_1, the estimated value of each articulator parameter completely agreed with its correct value; 2) in case of S_2, the estimated value included error components, ΔC_s=0.18° and ΔI_s=0.65°; and 3) no local maximum was observed near the optimum solution. Additionally, minimum distances $d_{\min}$ of contact points P_A, P_B and P_C increased monotonously as each of the protrusive movements proceeded. The difference in this increasing pattern of $d_{\min}$ between the two movements was not significant at every point. These results suggested that the proposed method could be clinically applicable for adjusting the articulator accurately.

Dental prostheses have to harmonize with patients' complex stomatognathic system [1-3,57-62]. Then simulation of patients' tooth excursions is necessary for both conventional and CAD-based designs of patients' functional occlusal surface. In an attempt to reflect patients' tooth excursions on the design of occlusal surface, commercially available dental CAD systems have been used several methods such as: 1) to check occlusal interferences using patients' functional occlusal impressions recorded during tooth excursions [33]; and 2) to measure patients' jaw movements in three dimensions [66-69]. The former impression-based check usually needs several steps such as: 1) to record patients' functional occlusal impression; 2) to digitize the impression for CAD; 3) to virtually superpose the impression with a dental prosthesis within CAD; and 4) to check occlusal contacts and interferences. This check has an advantage of high operationality, but does not necessarily reflect all aspects of tooth excursions. The latter motion tracking-based check, on the other hand, reflects every aspect of measured tooth excursions, but has to utilize an expensive 6-DOF jaw movement measurement device. The clinical use of such devises is usually time-consuming, too. Compared to these conventional check methods, the proposed virtual articulator-based check has advantages of high operationality and capability of simulating tooth excursions, but does not necessarily reflect every aspect of actual tooth excursions.

Finally, I would like to talk about the difference between conventional semi-adjustable articulators and the virtual counterpart. The proposed virtual articulator has the same capability as actual ones in the following senses that 1) it can reproduce the same tooth excursions, because it has the same adjustable parameters as actual ones; and 2) it enables us to check the articulation between opposing occlusal surfaces during tooth excursions. In addition, the virtual articulator has several inherent functions as follows, due to its virtuality,: 1) to visualize the distance between opposing occlusal surfaces by using a proximity mapping on the crown surface; and 2) to display an arbitrary cross section through dental arches in the intercuspal position or an eccentric jaw position. Conventional dental articulators, on the other hand, cannot have these functions. As suggested by Rekow (1996) [21], the virtual articulators capable of numerically describing patients' tooth excursions are suitable to telemedicine in dentistry, such as remote diagnosis of patients' occlusion and remote fabrication of dental prostheses.

3.7 Conclusion

In order to design optimal occlusal surface harmonized with patients' tooth excursions, our laboratory has been developing a dental CAD system, Vocs-2, equipped with a virtual articulator. To realize a customizable articulator within the CAD, this study proposed an advanced 3D registration-based method for automatically adjusting the articulator in accordance with patients' functional occlusal impressions. Computer simulations suggested that the proposed method has a capability of adjusting the virtual articulator on a clinically applicable level.

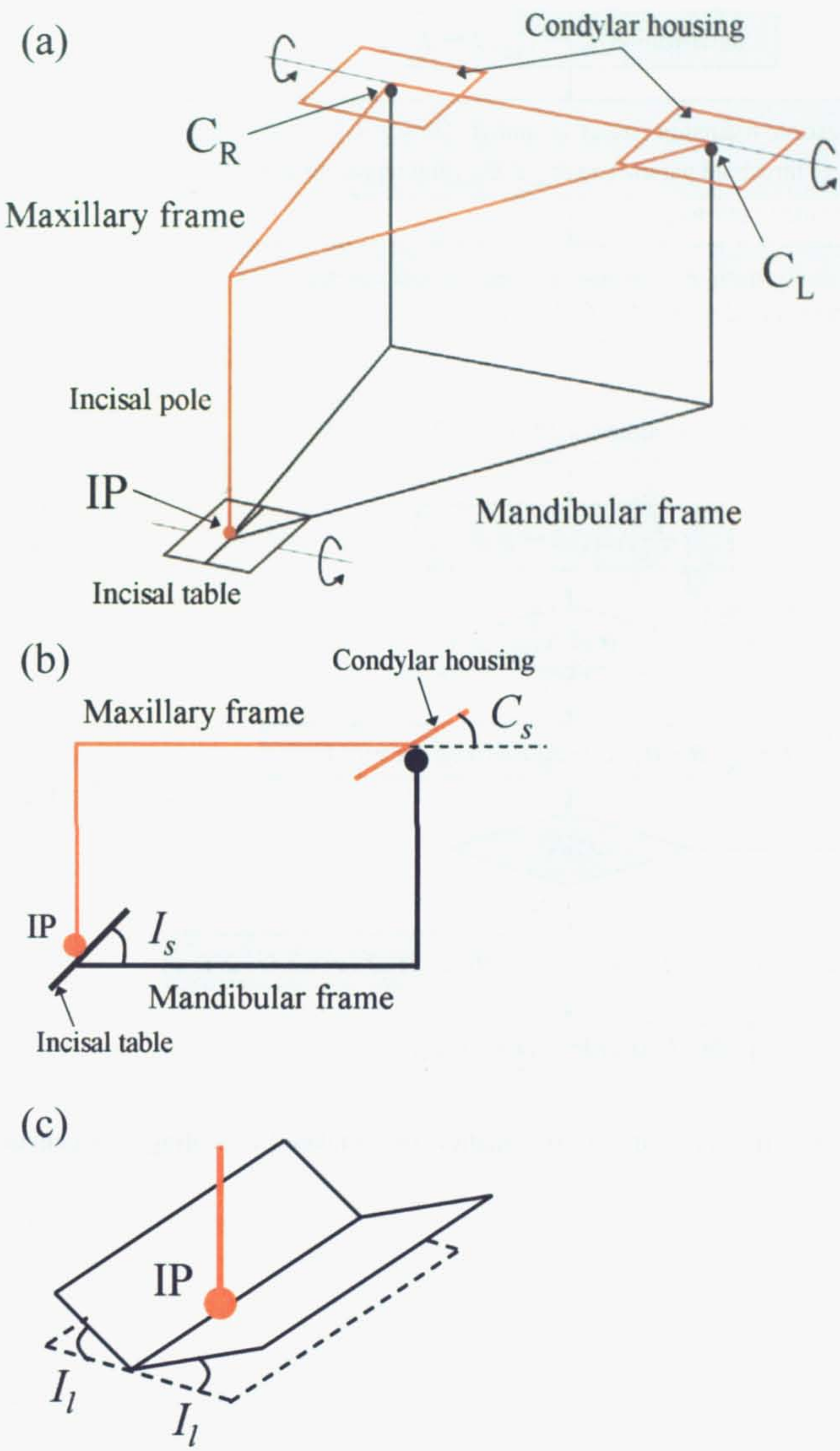


Figure 5 Virtual Articulator. (a) Computer model of articulator (b) Computer model of articulator (sagittal view) (c) Incisal table (enlarged view).

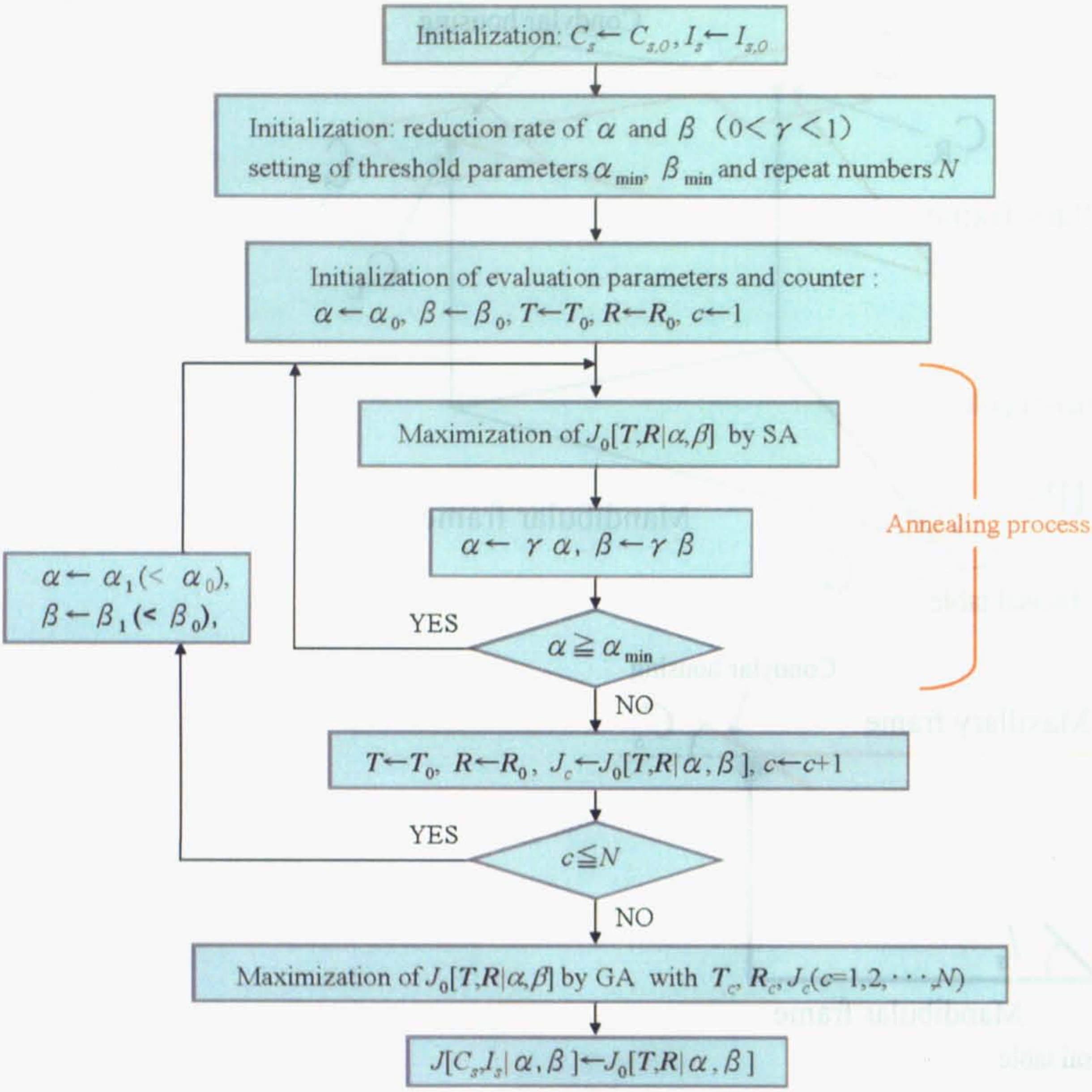


Figure 6 Flowchart of a superposing using a combination of simulated annealing and genetic algorithm.

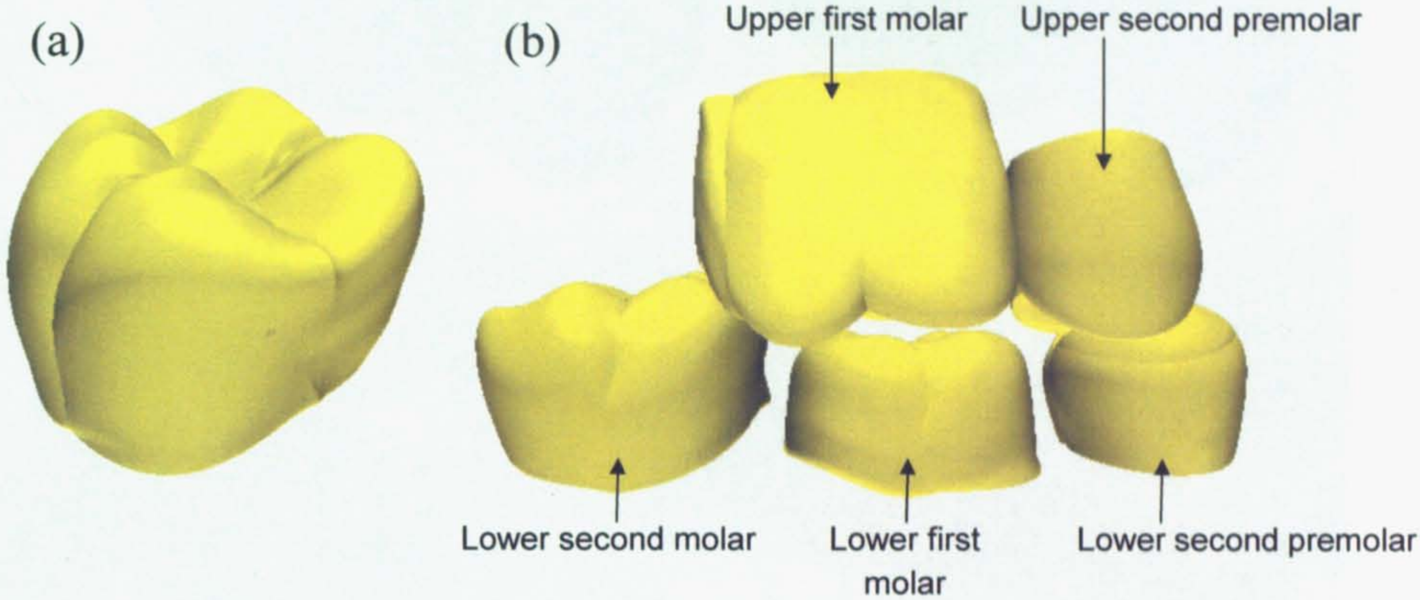


Figure 7 The empirical data of tooth model. (a) a crown model of the lower first molar, (b) intercuspated dental-arch model.

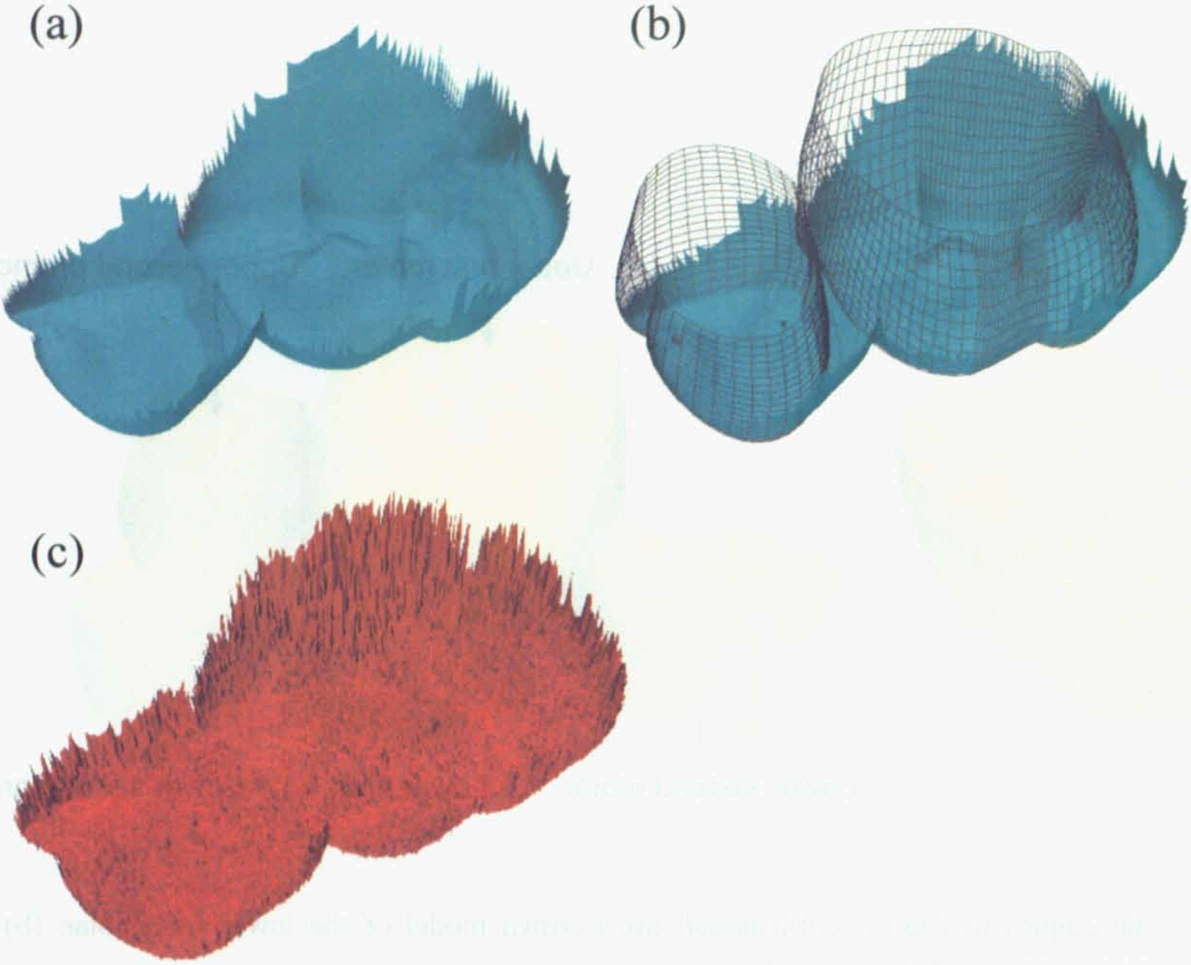
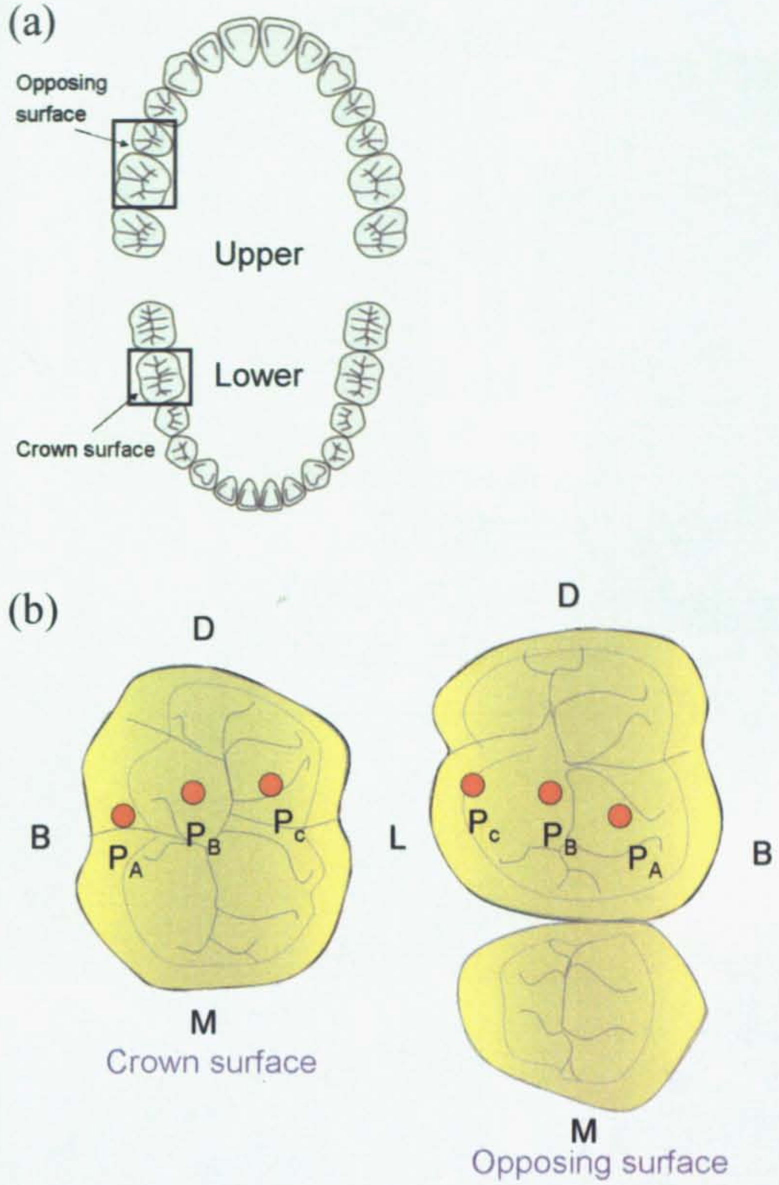
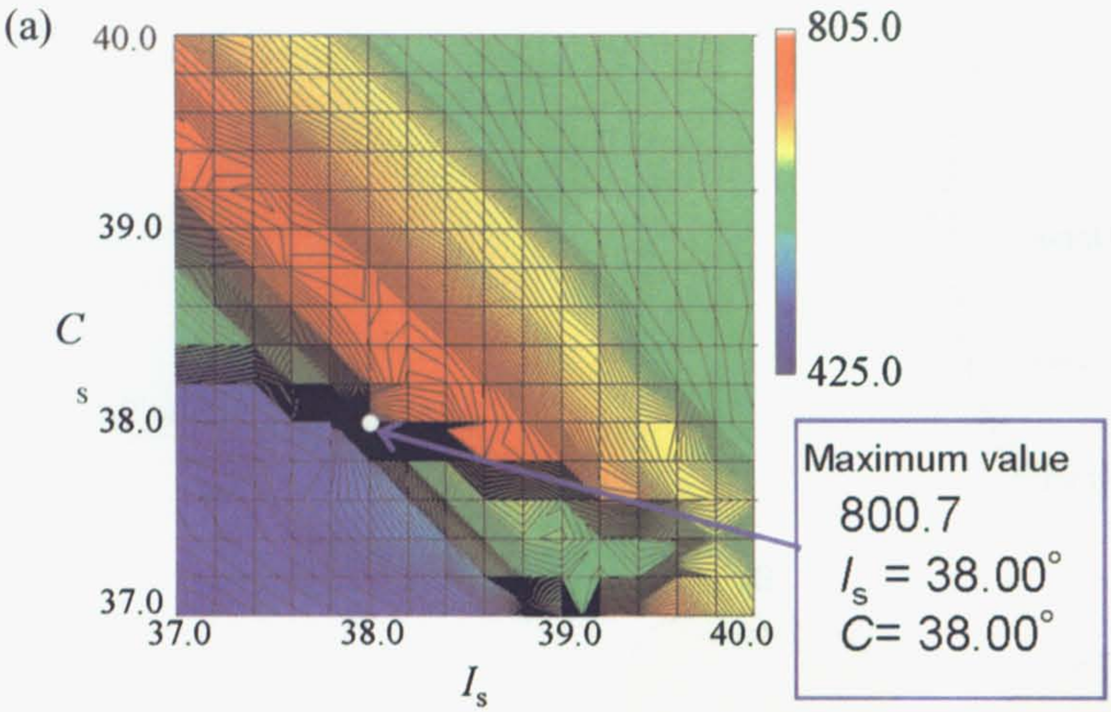


Figure 8 Virtual occlusal impressions. (a) a virtual impression S_1 , (b) the virtual impression S1 and opposing teeth (intercuspation), (c) a virtual impression S_2 which was created by adding Gaussian noise (SD = 0.1 mm) to S_1.



M: Mesial side, D: Distal side, B: Buccal side, L: Lingual side.

Figure 9 Created occlusal contact points on the occlusal surface of the crown. (a) location of crown surface and opposing surface in upper and lower dentitions, (b) occlusal view of crown surface and opposing surface.



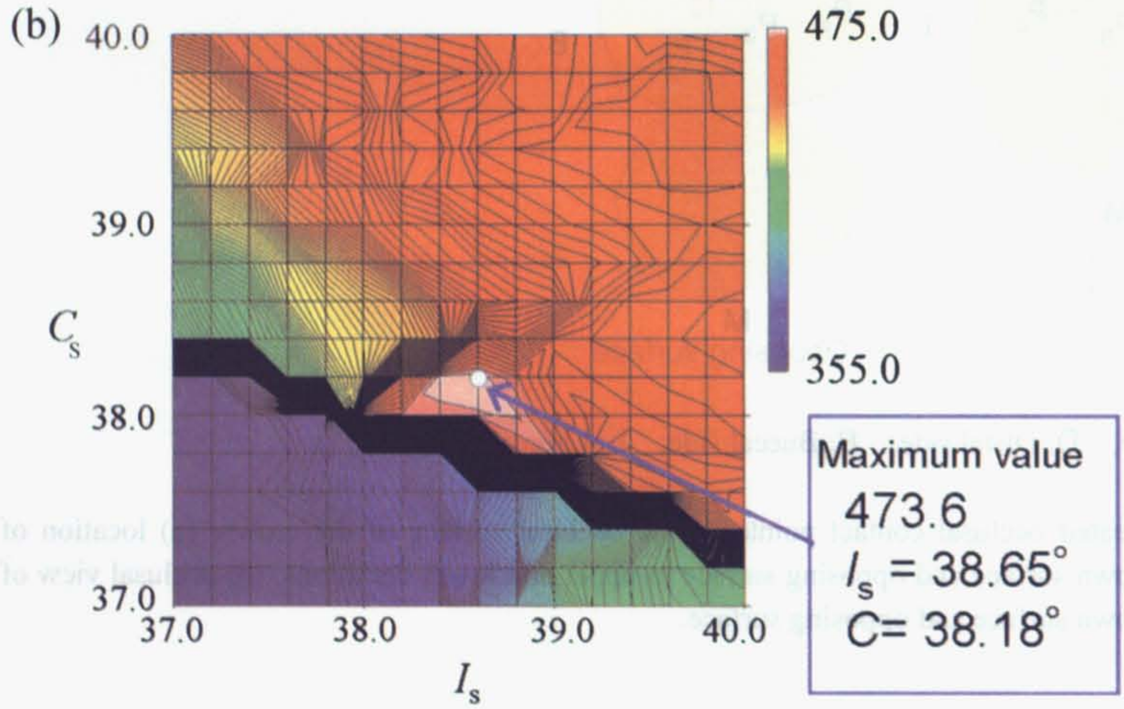
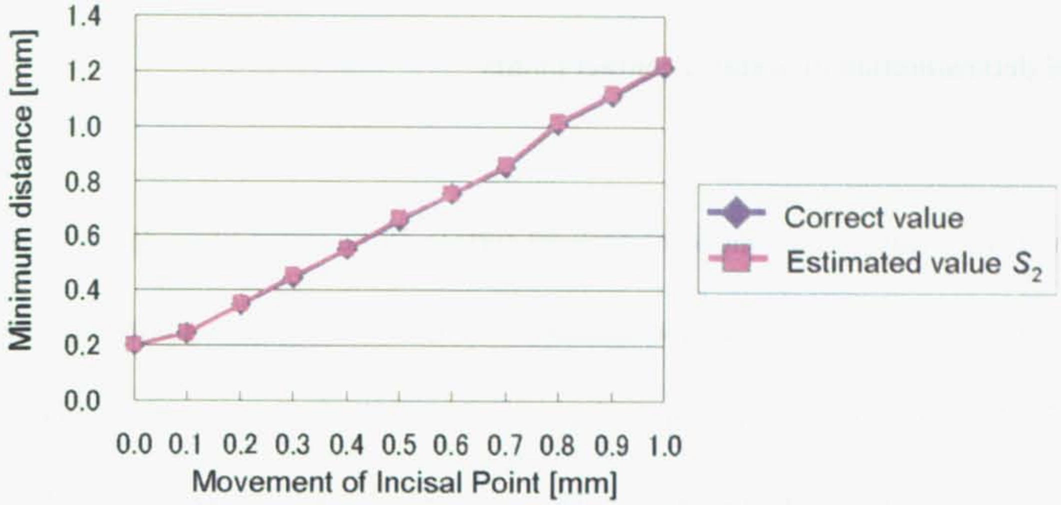
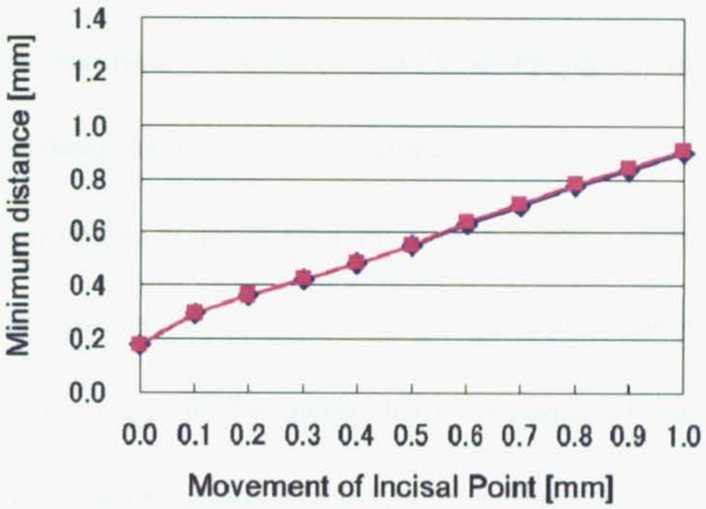


Figure 10 Two-dimensional pseudo-color visualization of function $J[C_s, I_s]$ with its vertical and transversal axes of C_s and I_s.

(a)



(b)



(c)

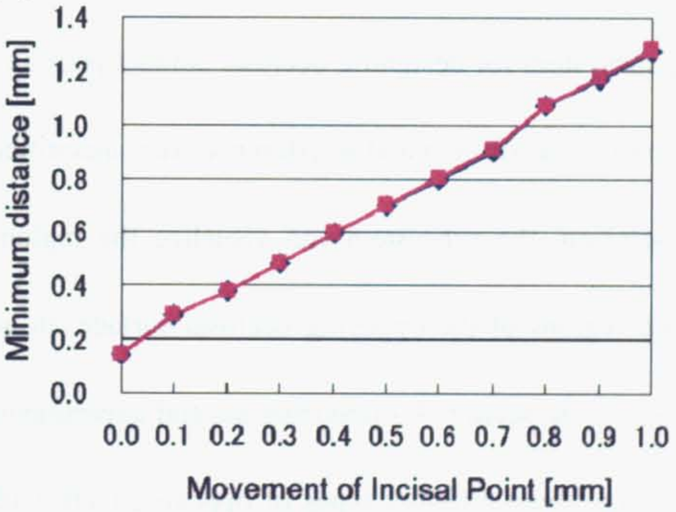


Figure 11 Minimum distances d_{min} of contact points P_A, P_B and P_C during two protrusive movements. (a) contact point P_A, (b) contact point P_B, (c) contact point P_C.

4. Computer-aided determination of occlusal contact points

4.1 Introduction

In order to obtain a natural and functional occlusal surface of the crown using dental CAD, we have to simulate not only the intercuspation, but also tooth articulation during gliding movements [1-3,57-62]. Then, this study proposed a virtual articulator capable of simulating patients' tooth excursions in the previous chapter. During tooth excursion, opposing occlusal surfaces separate or contact with each other. Their separation is referred to as the "disclusion" in dentistry, while the contact can be classified into two groups as follows: 1) natural contact; and 2) interferential contact from a clinical viewpoint [1,3]. When designing a patients' crown, dentists have to provide its occlusal surface with appropriate contacts both in the intercuspation and during tooth excursions, according to the diagnosis of tooth occlusion [1-3]. In order to assist the design of the occlusal contact, this study propose an advanced computer-assisted system, which can visualize whether each point of the opposing occlusal surface is appropriate or not as a contact point of the crown under design.

The next section describes an assisting subsystem for designing occlusal contact points of the crown surface. In order to evaluate occlusal contact, separation and interference were quantified as the "disclusion". By using the value of disclusion, the subsystem can visualize the regions suitable for occlusal contact and the interference regions of the opposing occlusal surface. In an attempt to validate a clinical applicability of this system, section 4.3 describes several experiments for designing the crown of a lower first molar using three different types of opposing teeth with different cusp angles. Subsequently, section 4.4 shows empirical results. Section 4.5 discusses clinical applicability of the assisting system from several perspectives. Finally, section 4.6 summarizes this chapter.

4.2 Computer-aided determinate of occlusal contact points

In order to assist in designing the occlusal contacts of a crown using dental CAD, this study propose a technique visualizing whether each point of the opposing occlusal surface is appropriate or not as a contact point. In addition, the system can visualize interference regions of the opposing surface in which the contact points must not be located in intercuspation. The visualization process is summarized as follows: 1) the operator sets an eccentric jaw position, in which the articulation is evaluated; 2) the positional relationship between the upper and lower teeth is computed in the designated jaw position; 3) the suitability as a contact point is evaluated at every point on the opposing surface; and 4) suitable regions and interference regions obtained on the opposing surface are visualized on the computer display.

In order to assess the suitability of a contact point, how to evaluate the displacement between the opposing occlusal surfaces was determined. A point on the crown surface, denoted as A, is assumed to contact with the opposing surface in the intercuspal position. The contact point of the opposing surface is denoted as B. The normal vector of the opposing surface at B is denoted as $\boldsymbol{n}$. The displacement vector of A from the intercuspal position to an eccentric position is denoted as $\boldsymbol{m}$. Vector $\boldsymbol{m}$ can be decomposed into two rectangular components $\boldsymbol{m}_{\mathrm{n}}$ and $\boldsymbol{m}_{\mathrm{o}}$, which are defined as an orthogonal projection of $\boldsymbol{m}$ on $\boldsymbol{n}$ and the residual component, respectively, i.e., $\boldsymbol{m}=\boldsymbol{m}_{\mathrm{n}}+\boldsymbol{m}_{\mathrm{o}}$. Vector $\boldsymbol{m}_{\mathrm{n}}$ can be interpreted as the separation vector of the opposing surfaces at contact point B. Then, the separation was quantified with the inner product of $\boldsymbol{m}$ and $\boldsymbol{n}$, denoted as $D\equiv(\boldsymbol{m}, \boldsymbol{n})$ (Fig. 12), which can be computed at every point of the opposing surface. A contact point of the crown can be created in the three different regions of the opposing surface where $D>0$, $D=0$ and $D<0$. In case of $D>0$, the contact point is separated from the opposing surface in the designated eccentric position, while in case of $D=0$ or $D<0$, the point remains in contact with or interferes with the opposing surface, respectively.

The system can visualize the opposing surface in the form of a wire-frame representation, which consists of triangular patches, while displacement D is evaluated in relation to every patch in several eccentric positions. The design procedure is summarized as follows: 1) to designate less than or equal to three tooth excursions which have to be considered seriously in the design of crown; 2) to input motion parameters, such as C_s, I_s, I_l and motion distance, regarding the designated movements; 3) to input required displacement D_R, which is determined by a dentist, for each eccentric position; 4) to compute the areas satisfying all required conditions, where we can select occlusal contact points; 5) to visualize the areas on the opposing surface in an attempt to assist subsequent contact point determination; and 6) to determine contact points of the crown by using the visualization obtained in the previous step.

4.3 Materials and Methods

The computer-aided design of the contact points proposed in the previous section was implemented in C-language on a personal computer (Microsoft® Windows® XP, Intel® Celeron® 2.4GHz), and applied it to the design of a crown for the lower right first molar. This section provides us with empirical data of teeth and protocols of two different experiments carried out for evaluating the influence of tooth shape and excursion on the performance of the system.

As empirical data of tooth shape, this study employed three different intercuspated dental-arch models, including the lower second premolar, the lower first molar (abutment), the lower second molar, the upper first molar and the upper second premolar (opposing teeth). Regarding upper teeth, three different models with different buccal cusp angles (moderate, sharp and dull) were prepared, while a single lower teeth model intercuspated with these upper models was prepared, as shown in Fig. 13. The models were obtained by digitizing plaster models four times larger than life size.

Firstly an experiment for designing a crown for the abutment was carried out using opposing teeth with a moderate cusp angle. Its procedure is summarized as follows: 1) initialization (scale transformation of the library model, adjustment of the position and orientation relative to the abutment, and adjustment of the margin line); 2) design of proximal and distal surfaces; 3) rough design of occlusal surface; and 4) adjustment of occlusal contact points, described in the previous section. The locations of five different occlusal contact points (P_1-P_5) were roughly decided on the occlusal surface of the crown in an attempt to satisfy several required conditions under the theory of tripodism, as illustrated in Fig. 14.

I selected three typical gliding movements such as protrusive, right lateral and left lateral movements for simulation of tooth excursions. The virtual articulator was adjusted in an average manner as $C_s = 40$ °, $I_s = 70$ ° and $I_l = 30$ °.

The articulator can simulate a tooth excursion by moving incisal pole IP from the intercuspal position to an eccentric position. The motion distance of incisal pole IP was set at 1 mm. The required displacement D_R was set at 0.2 mm. Design policies of the contact points were as follows: G1 (point P_1): the contact points should be in contact with the opposing surface during the right lateral movement, but should be separated during other excursions; G2 (points P_2, P_4 and P_5): the contact points should be separated from the opposing surface during every tooth excursion; G3 (point P_3): the contact point should be in contact with the opposing surface during the left lateral movement, but should be separated during other excursions.

Secondly an experiment for designing a crown was carried out using two different opposing teeth with sharp and dull cusp angles, in an attempt to verify that our system can be applied to various clinical cases with a wide variety of tooth contours and gliding movements. Then, the experiment employed two different patterns of gliding movements by adjusting the virtual articulator as follows: Pattern 1: $C_s = 45$ °, $I_s = 75$ ° and $I_l = 35$ °; Pattern 2: $C_s = 35$ °, $I_s = 65$ ° and $I_l = 25$ °. The motion distance was set at 1 mm. The required displacement D_R was set at 0.2 mm. Design policies of the contact points were "All contact points have to avoid interferences during all tooth excursions". The empirical procedure was the same as that of the previous experiment.

In order to verify points P_1-P_5 to satisfy the required conditions mentioned above, the minimum distance, denoted as d_{min}, between every contact point and its opposing surface during tooth excursions was computed. The experiment assumed that if 0.2 mm $\leq d_{min}$ mm during a certain tooth excursion, the contact point is separated from the opposing surface, while if 0 mm $\leq d_{min} <0.2$ mm without interference, the point remains in contact, where a threshold of 0.2mm was determined by considering tooth mobility and mandibular deformation during lateral excursion [70].

4.4 Results

The results of the first experiment are as follows. Figure 15 visualizes the occlusal surfaces of the crown and the opposing teeth in intercuspation. The blue colored areas on the opposing tooth designate the regions at which contact points of G1, G2 and G3 are permissible to touch in intercuspation. The red colored areas on the opposing tooth, on the other hand, designate the regions at which every contact point should not touch in intercuspation. According to these guidelines, the positions of all contact points were determined on the occlusal surface of the crown, as shown in Fig. 16 and Fig. 17. Figure 16 illustrates the obtained occlusal surface and its "near-contact regions" in the intercuspal position and other eccentric jaw positions, where the near-contact regions are defined as the areas being less than or equal to 0.2 mm distant from the opposing surface. In intercuspation (Fig. 16-a), the contact points could be successfully created on the occlusal surface of the crown within the predetermined areas (Fig. 14). In the protrusive position (Fig. 16-b), every contact point was separated from the opposing surface. In the right lateral position (Fig. 16-c), P1 of G1 alone touched at the opposing surface, while in the left lateral position (Fig. 16-d), P3 of G3 touched. No cuspal interference was observed in every eccentric jaw position.

Figure 17 shows the values of d_{min} during tooth excursions at every contact point P_i (i=1,2,...,5). In the protrusive movement (Fig. 17-a), the value of d_{min} increased monotonously in proportion to the moved distance of IP from the intercuspal position. In the right lateral movement (Fig. 17-b), the value of d_{min} at points belonging to G2 and G3 increased in the same manner as that of Fig. 17-a, while the value of d_{min} at P_1 of G1 remained within 0.2 mm throughout the movement. In the left lateral movement (Fig. 17-c), the value of d_{min} at points belonging to G1 and G2 also increased, while the value of d_{min} at P_3 of G3 remained within 0.2 mm throughout the movement.

The results of the second experiment are as follows. Figure 18 visualizes the occlusal surfaces of the crown and the opposing teeth in intercuspation. The blue colored areas on the opposing tooth designate the regions at which every contact point is permissible to touch in intercuspation. The red colored areas on the opposing tooth, on the other hand, designate the regions at which every contact point should not touch in intercuspation. Among the results, the study focus on that of a case, shown in Fig. 18-c, with the empirical conditions possibly causing occlusal interference. According to the guideline (Fig. 18-c), the position of all contact points were determined on the occlusal surface of the crown, as shown in Fig. 19 and Fig. 20. Figure 19 illustrates the obtained occlusal surface and its "near-contact regions" in the intercuspal position and other eccentric jaw positions. In intercuspation (Fig. 19-a), the contact points could be successfully create on the occlusal surface of the crown within the predetermined areas (Fig.14). In the protrusive position (Fig. 19-b), every contact point was separated from the opposing surface. In the right lateral position (Fig. 19-c), P_1 and P_2 of G1 touched at the opposing surface, while in the left lateral position (Fig. 19-d), P3 of G3 touched. No cuspal interference was observed in every eccentric jaw position.

Figure 20 shows the values of d_{min} during tooth excursions at every contact point. In the protrusive movement (Fig. 20-a), the value of d_{min} increased monotonously in proportion to the moved distance of IP from the intercuspal position. In the right lateral movement (Fig. 20-b), the value of d_{min} at points belonging to P_3, P_4 and P_5 increased in the same manner as that of Fig. 20-a, while the value of d_{min} at P_1 and P_2 remained within 0.2 mm throughout the movement. In the left lateral movement (Fig. 20-c), the value of d_{min} at points belonging to P_1, P_2, P_4 and P_5 also increased, while the value of d_{min} at P_3 remained within 0.2 mm throughout the movement.

4.5 Discussion

First I would like to summarize empirical results and to evaluate whether the obtained occlusal surfaces satisfy all the required conditions or not. In the first experiment, the results indicated the facts that 1) in protrusive movements, points in every group were separated from the opposing surface by a distance of more than or equal to 0.2 mm; 2) in right lateral movements, points in groups G2 and G3 showed the same separation, while every point in G1 remained in close or contact ($d_{min} < 0.2$ mm); 3) in left lateral movements, points in G1 and G2 were separated from the opposing surface by a distance of more than or equal to 0.2 mm, while the point in G3 remained in close or contact; and 4) no cuspal interference was observed during every tooth excursions. In the second experiment, no cuspal interference was observed during every tooth excursions. Thus, the obtained occlusal surfaces of the crown always satisfied all required conditions in every experiment. In the second experiments, several combinations of morphological and kinematic conditions which expected to encounter in clinic were simulated, including those with a high possibility of causing occlusal interferences. Even in such crucial cases, the occlusal surfaces of the crown designed under the support of the system were satisfactory with no interference. These results suggested that the system assisting to design occlusal surfaces could be useful for a wide variety of clinical cases.

Next, I would like to talk about clinical importance of assisting the design of interfere-free occlusal surfaces. The occlusal surface has several important functions such as: 1) the determination of the intercuspal position; 2) tooth support in the occlusal position; and 3) compression of food during chewing [1-3,57-62]. These functions can be fully achieved by not only tooth anatomy, but other components of the stomatognathic system, such as the periodontium, the neuromuscular system and the temporomandibular joint, interrelated with each other. Then, one of these components unsuitable to stomatognathic functions could cause destructive effects to other components. For instance, occlusal interference is a cause of occlusal trauma, and could trigger temporomandibular joint disorders [1-3, 59]. In order to avoid such negative effects of malocclusion, several kinematic theories concerning functional occlusal surfaces have been proposed [1,3,71-75], such as Gysi's facet and axis theories [71] and Slavicek's sequential occlusion [72]. Clinical implementation of these theories, however, has been limited primarily due to the absence of clinical techniques developed under the theorems. For instance, the theory of tripodism, where every cusp of molars should have three different contact points in intercuspation, was proposed [1,3]. This cannot easily be applied in clinic because occlusal interferences occur more frequently by increasing the number of contact points, particularly in critical conditions. Even in such critical cases, the system enables us to easily design interference-free occlusal surfaces, because the system can visualize both suitable and interference regions on the opposing surface for locating the contact points. In this respect, the system can be considered a powerful tool for advanced occlusal theorems to be applied in clinic.

Finally, I would like to talk about prerequisites for CAD-based optimum design of occlusal surface, and then to access our system from these respects. To improve time-consuming and inaccurate determination of occlusal contact points in dental CAD, we need an advanced computer-aided system assisting to design an optimal occlusal surface for each patient. In order to optimize the number and location of contact points of the crown, this study suppose that such assisting system should have at least following functions: 1) to compute tooth articulation during tooth excursions; 2) to evaluate the inter-surface distance between the opposing teeth during the excursions (interference, contact or separation); and 3) to visualize the evaluation results for the operator to determine the location of contact points. In an attempt to reply these prerequisites, the following functions were added in the system: 1) a virtual articulator; 2) an evaluation of the amount of separation or interference between the opposing occlusal surfaces during tooth excursions; and 3) a visualization of the upper surface areas in which occlusal contact points should be located in intercuspation. These functions appear to be a materialization of the prerequisites. Additionally, these functions were verified to be effective for optimum design of occlusal contact points for a wide variety of clinical cases, as mentioned previously.

4.6 Conclusion

In order to assist the design of the occlusal contact points, this study propose a advance assisting system for dental CAD system, which can visualize whether each point of the opposing occlusal surface is appropriate or not as a contact point of the crown designed. In an attempt to evaluate applicability of the system, several experiments for designing the crown of a lower first molar were carried out using three different types of opposing teeth with different cusp angles. The results demonstrated that all contact points located within the designated regions completely satisfied the required conditions regarding contact and separation during every tooth excursion. It is strongly suggesting that our assisting system has wide range of clinical applicability.

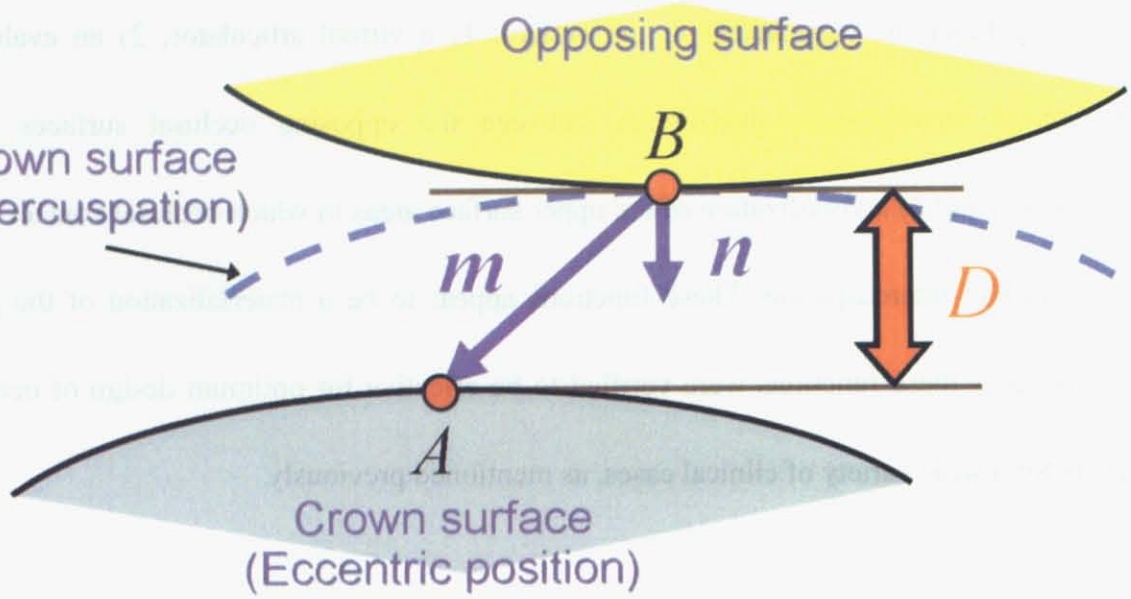


Figure 12 Quantification of disclusion during tooth excursion. *A*: The contact point of the crown surface; *B*: The contact point of the opposing surface; ***m***: The displacement vector of *A* from the intercuspal position to the eccentric position; ***n***: The normal vector of the opposing surface at *B*; and *D*: the displacement between the opposing occlusal surfaces.

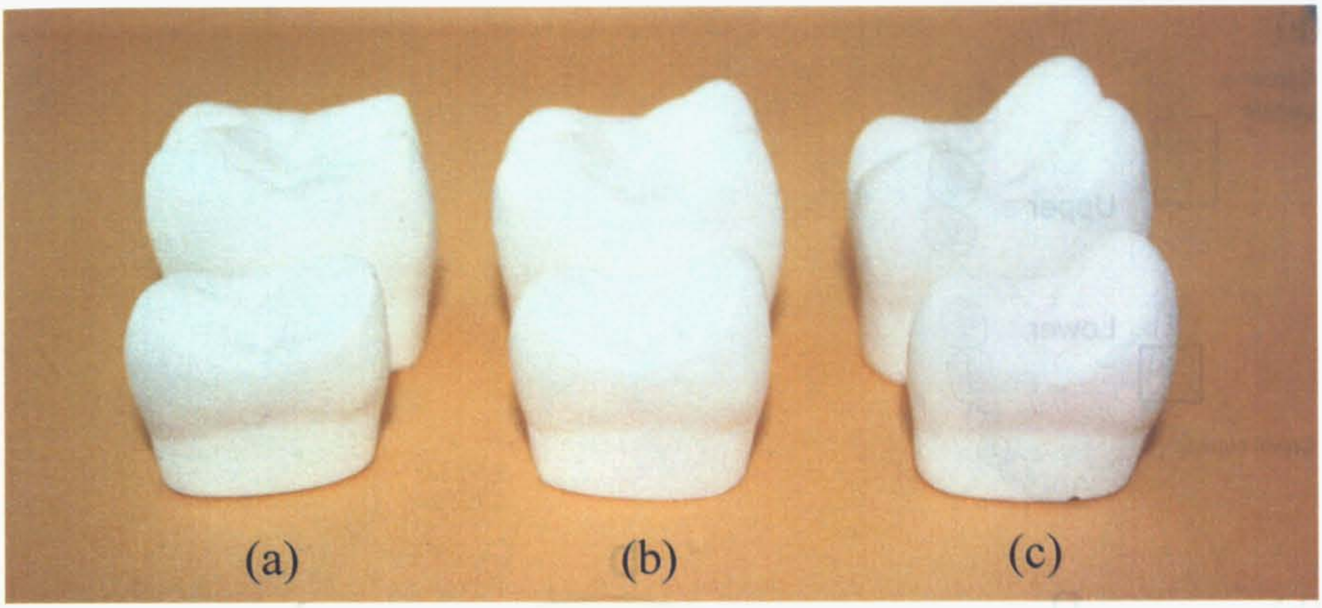
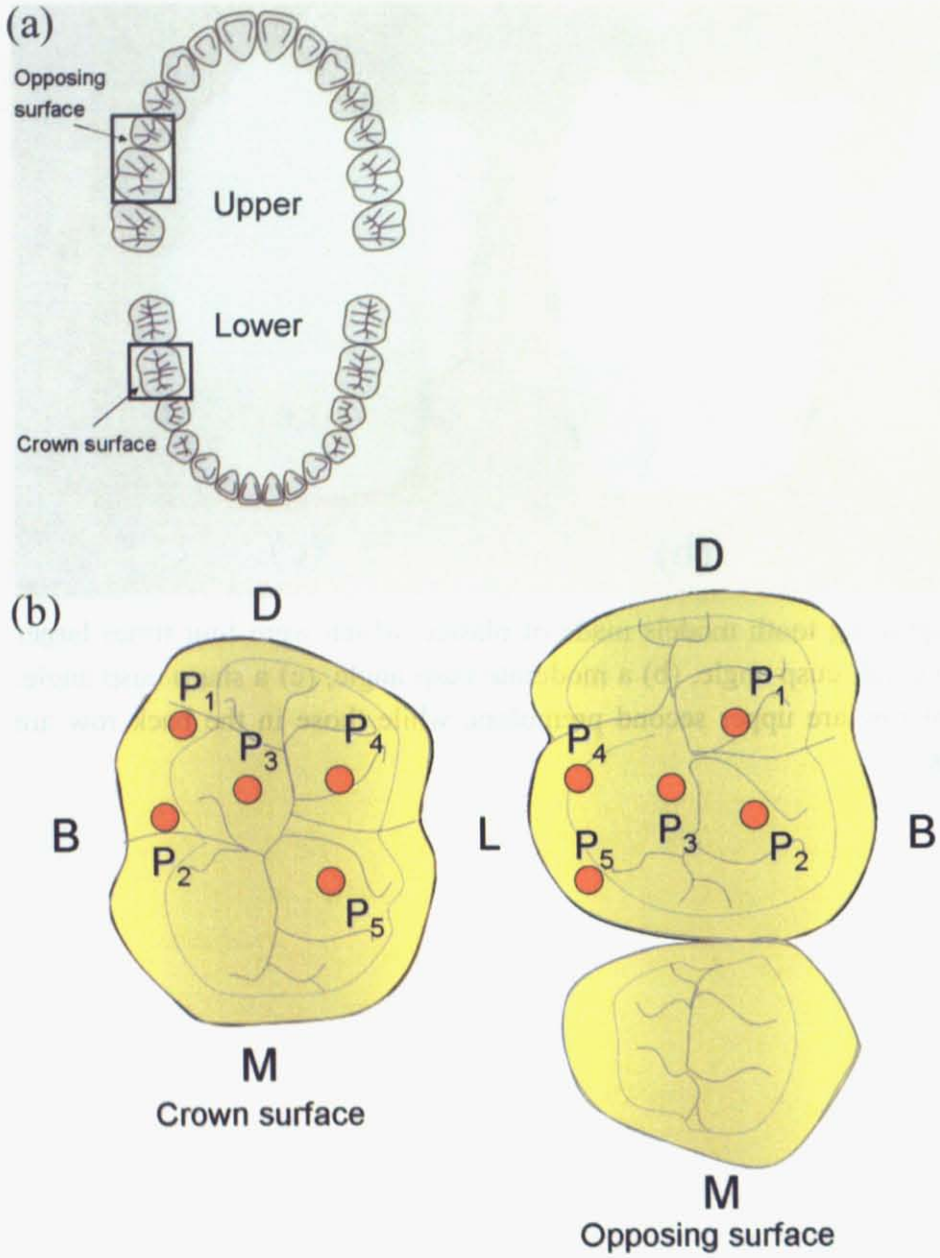
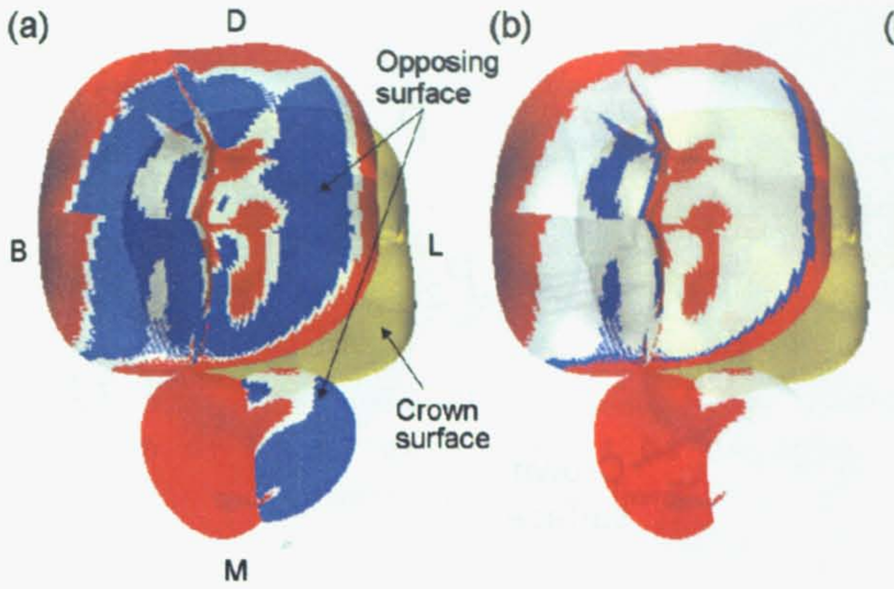


Figure 13 Three different opposing tooth models made of plaster, which were four times larger than life size. (a) a dull cusp angle, (b) a moderate cusp angle, (c) a sharp cusp angle. Teeth in the front row are upper second premolars, while those in the back row are upper first molars.



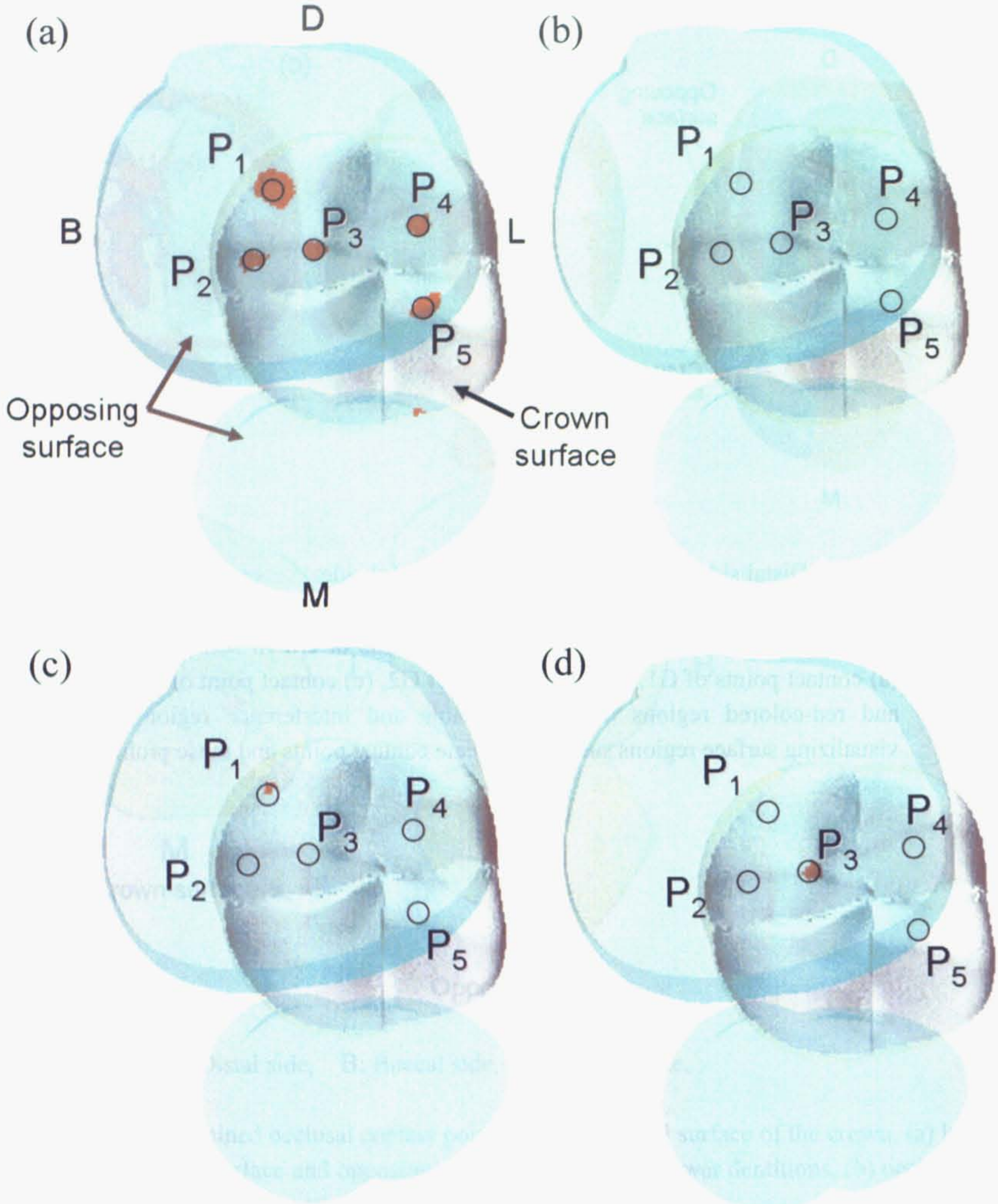
M: Mesial side, D: Distal side, B: Buccal side, L: Lingual side.

Figure 14 Predetermined occlusal contact points on the occlusal surface of the crown. (a) location of crown surface and opposing surface in upper and lower dentitions, (b) occlusal view of crown surface and opposing surface.



M: Mesial side, D: Distal side, B: Buccal side, L: Lingual side.

Figure 15 Tooth regions suitable for occlusal contact points of crown surface in experiment 1. (a) contact points of G1, (b) contact point of G2, (c) contact point of G3. Blue-colored and red-colored regions designate suitable and interference regions, respectively, visualizing surface regions suitable to create contact points and those prohibited.



M: Mesial side, D: Distal side, B: Buccal side, L: Lingual side.

Figure 16 Near contact regions on the occlusal surface of the crown in experiment 1. (a) intercuspal occlusal position, (b) protrusive position (1mm), (c) lateral position (right, 1mm), (d) lateral position (left, 1mm).

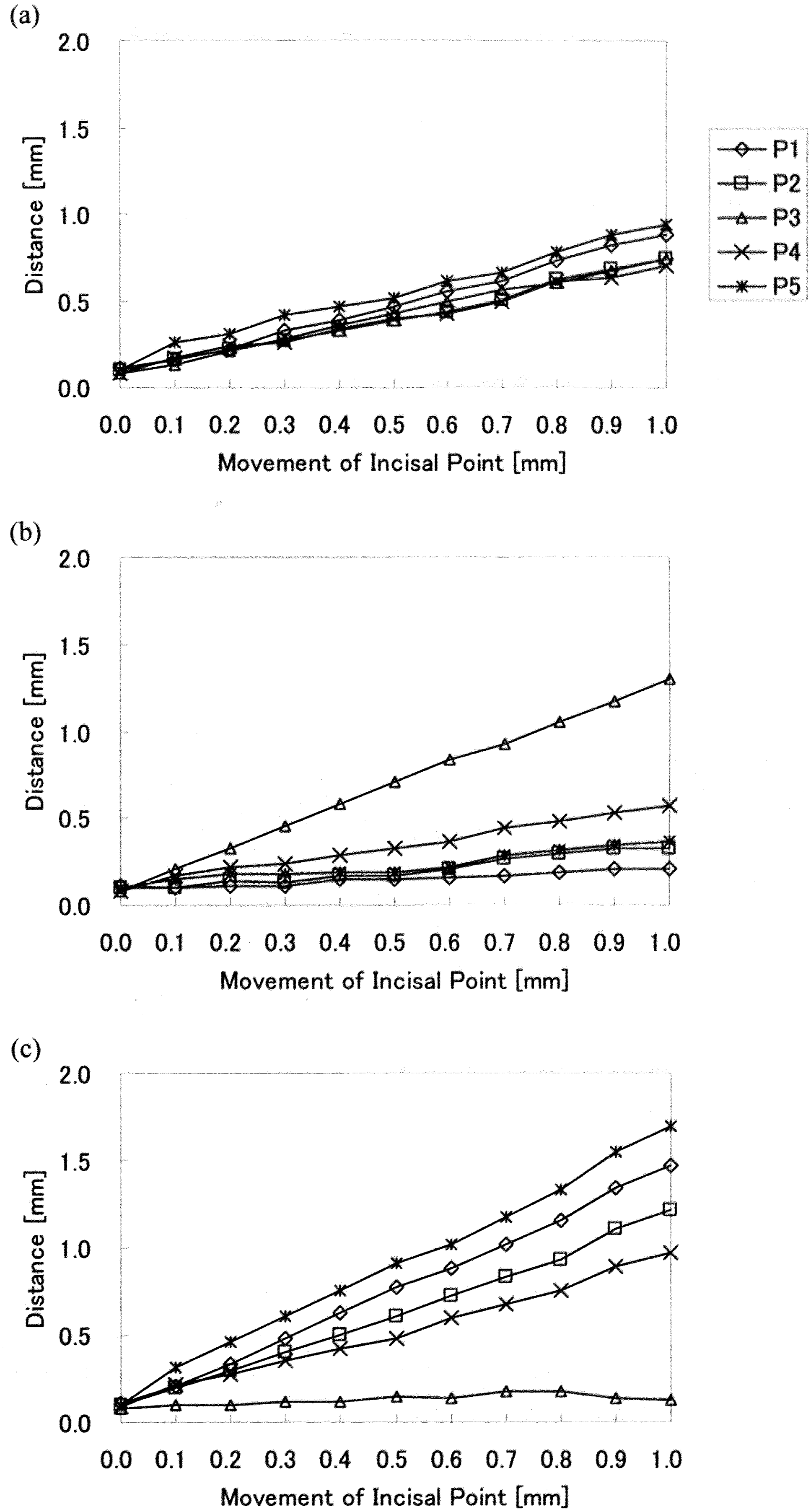
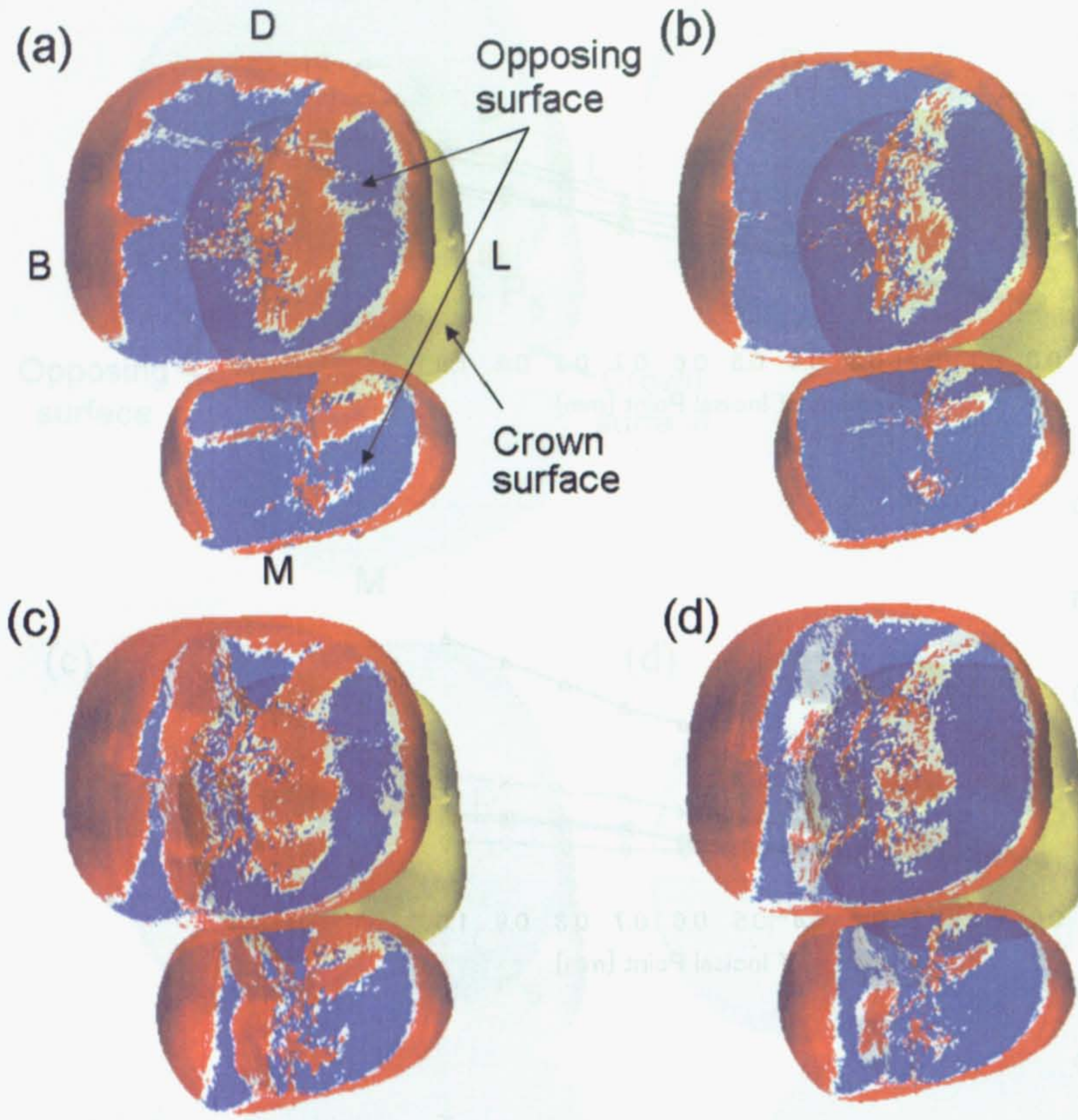
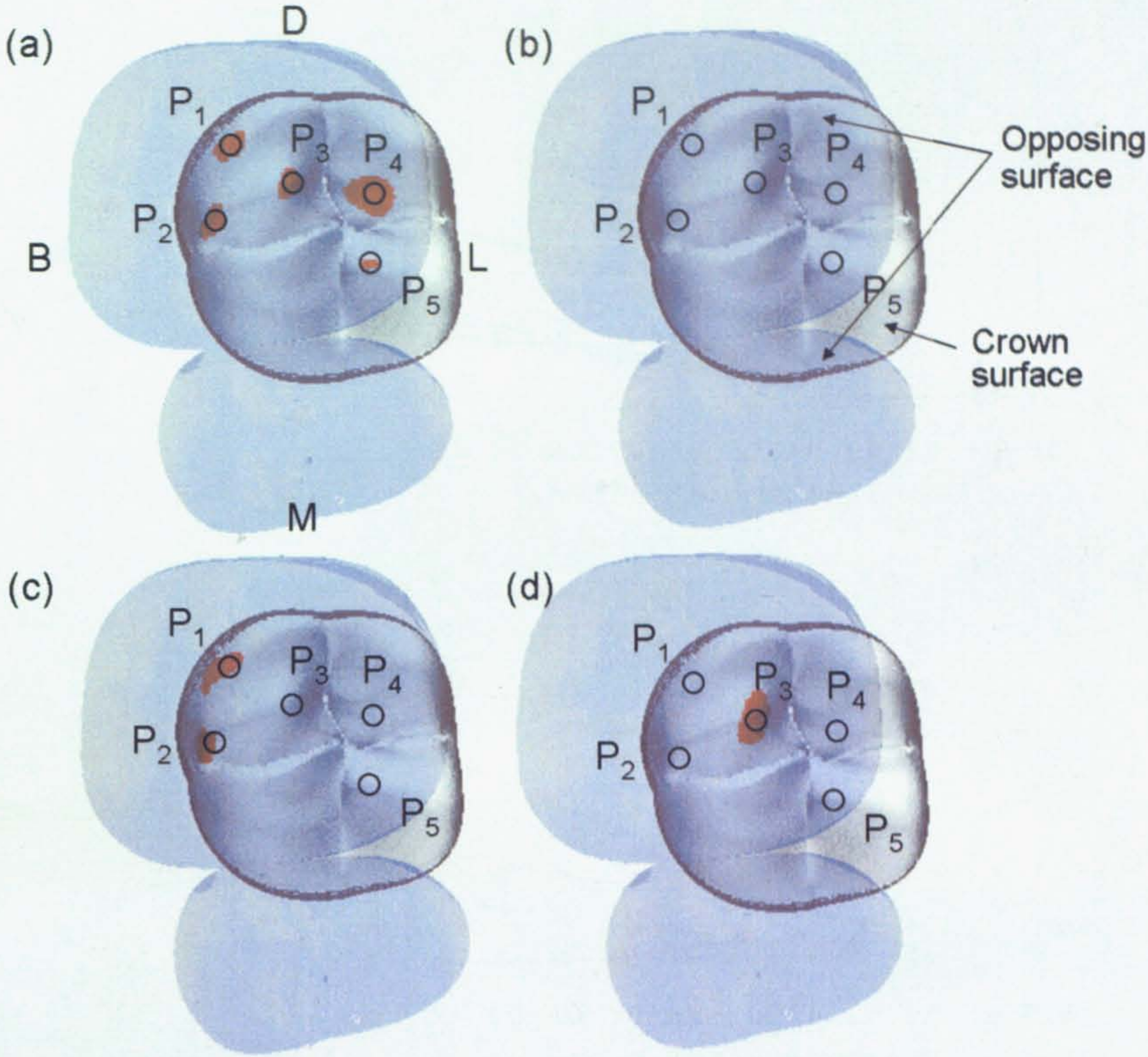


Figure 17 Disclusion during tooth excursions in experiment 1. (a) protrusive movement, (b) right lateral movement , (c) left lateral movement.



M: Mesial side, D: Distal side, B: Buccal side, L: Lingual side.

Figure 18 Tooth area suitable for occlusal contact point in experiment 2. (a) opposing teeth with a dull cusp angle and guide pattern 2, (b) opposing teeth with a dull cusp angle and guide pattern 1, (c) opposing teeth with a sharp cusp angle and guide pattern 2, (d) opposing teeth with a sharp cusp angle and guide pattern 1. Blue-colored and red-colored regions designate suitable and interference regions, respectively.



M: Mesial side, D: Distal side, B: Buccal side, L: Lingual side.

Figure 19 Near contact regions on the occlusal surface of the crown in experiment 2. (a) intercuspal occlusal position, (b) protrusive position (1mm) , (c) lateral position (right, 1mm) , (d) lateral position (left, 1mm).

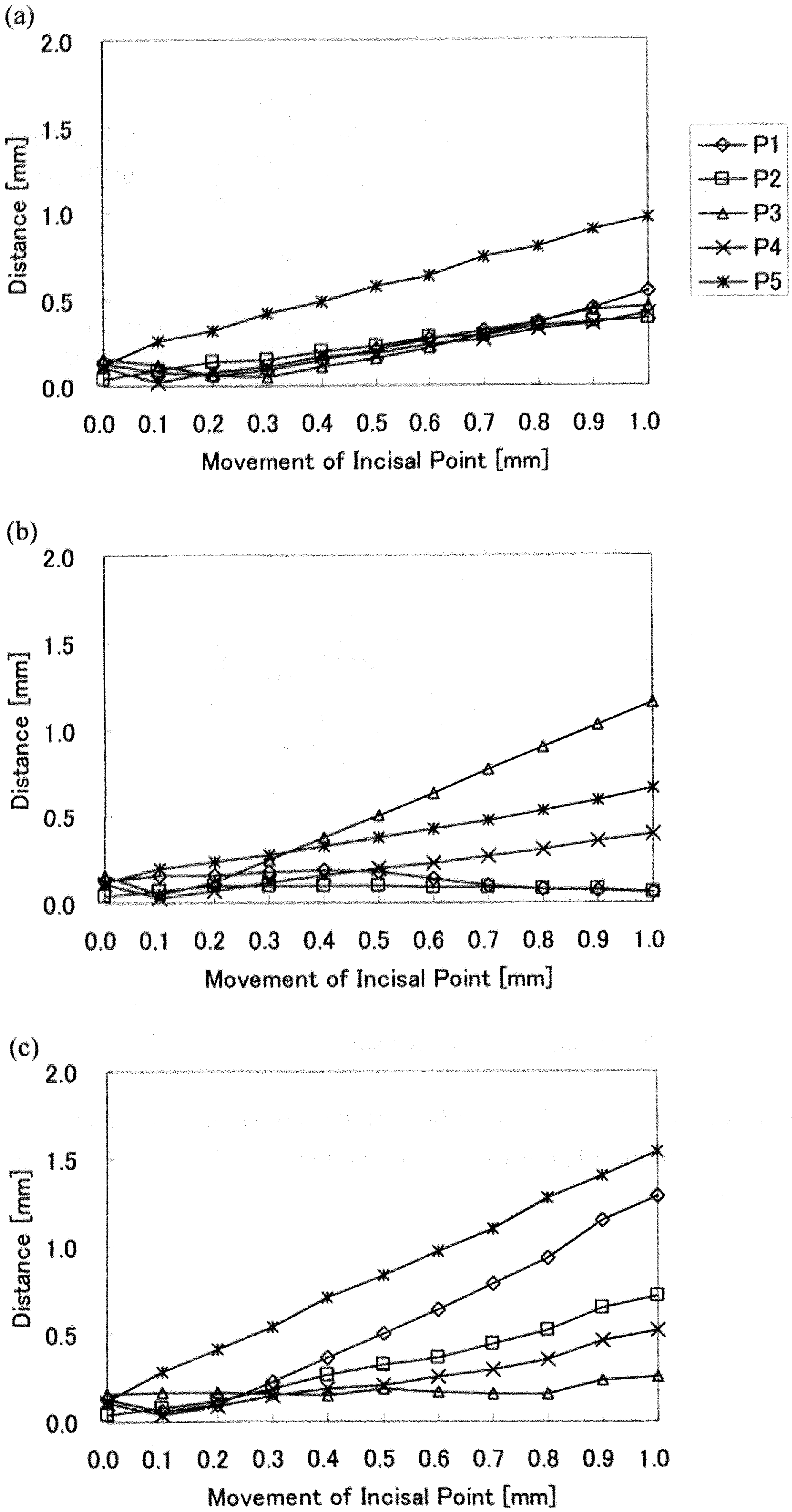


Figure 20 Disclusion during tooth excursions in experiment 2. (a) protrusive movement, (b) right lateral movement , (c) left lateral movement.

5. Concluding remarks

The overall objective of this thesis is to establish a methodology materializing a semi-automatic and objective design of functional occlusal surfaces in accordance with patients' tooth excursions. In order to achieve this, a sequence of studies was conducted in the following steps described in chapter 1.

1. *Development of dental 3-D CAD system, "Vocs-2" (Chapter 2)*

In order to establish an assisting technology for designing of occlusal contact points, a trial dental 3-D CAD system, Vocs-2, have been developed. This system has two distinct features of a tooth model with both surface- and solid-descriptions and a partial metamorphosis operator, while conventional dental CAD systems employ only a tooth model with surface description. These features achieved a detailed design of crown's occlusal surfaces with natural and functional contour, without loss of operationality. The solid model enables us to easily compute the inter-surface distance and interference between opposing occlusal surfaces. Such merits are advantageous particularly in a real-time visualization of the inter-surface distance map and an automatic elimination of cusp interference.

2. *Simulation of patients' tooth excursions (chapter 3)*

In order to design functional occlusal surfaces, dental CAD systems have to simulate not only the intercuspation, but also tooth articulation during excursions. Then, this study proposed a virtual articulator capable of simulating patients' tooth excursions. To realize a customizable articulator, this study proposed an advanced 3D-registrasion-based method for automatically adjusting the articulator in accordance with patients' functional occlusal impressions. Computer simulations suggested that the proposed method has a capability of adjusting the articulator with accuracy on a permissible level for clinical applications.

3. *Computer-Aided determination of occlusal contact points (Chapter 4)*

Design of complicated occlusal surfaces is of primary importance in dental CAD, considering its crucial functions in patients' stomatognathic system. In particular, the location of contact points in the intercuspal position is essential to obtain a functional occlusal surface without interference. Previous interfere-free design, however, has been done on a trial-and-error basis by using visual inspection. In order to improve such time-consuming and inaccurate procedure into a semi-automatic and accurate one based on quantitative evaluations, two difference functions were developed for dental CAD system such as 1) a virtual dental articulator, and 2) proximity mapping on the crown surface relative to its opposing occlusal surface. Subsequently, this study proposes a computer-aided system for assisting the determination of occlusal contact points employing the proximity mapping on the opposing surface. The system can designate such regions, which can be estimated from contour of the opposing occlusal surfaces and their relative movements simulated by using the virtual articulator. In an attempt to evaluate applicability of our system, several experiments for designing the crown of a lower first molar were carried out using three different types of opposing teeth with different cusp angles. The results demonstrated that all contact points located within the designated regions completely satisfied the required conditions regarding contact and separation during every tooth excursion. All these strongly suggested that our assisting system has a wide range of clinical applicability.

Consequently, I established an effective methodology materializing a semi-automatic and objective design of functional occlusal surfaces in accordance with patients' tooth excursions. This study is, however, to merely open a door to realize an ultimate dental 3D CAD capable of assisting the design from all aspects of kinesiology, material science, esthetics, oral hygiene and biology. Considering recent development of the information and communications technology, such an ideal CAD system is expected to be realized in the near future. I expect that this study would become an impetus to development almighty dental CAD systems.

Acknowledgement

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