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Original

Occlusion accuracy of restorations and removable partial dentures fabricated using the impression under occlusal force with functionally generated path recording

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Abstract: To evaluate the occlusion accuracy of a novel impression technique, excessively high occlusion and the occlusal contact area during lateral movements were compared between metal restorations (restorations) and removable partial dentures (RPDs) fabricated using conventional and novel techniques. Both restorations and RPDs were fabricated on the simulation model with the precise displacement of the remaining teeth and soft tissue. For the novel technique, functionally generated path (FGP) recording and impression under occlusal force were simultaneously performed using a custom tray with an FGP table. For the two conventional techniques, definitive casts were mounted on an average value articulator and a semi-adjustable articulator in the typical manner. Prostheses were placed on the simulation models, and excessively high occlusion in the intercuspal position and occlusal contact areas during lateral movements were measured. Statistical analyses were performed using Kruskal-Wallis and Steel-Dwass tests (α = 0.05). For both prostheses, conventional techniques showed significantly higher occlusion in the intercuspal position than the novel technique. Moreover, the new technique demonstrated better guidance contact during lateral movements than conventional techniques. This novel technique can be recommended for the fabrication of highly accurate prostheses with appropriate occlusal contact without corrections at delivery.

Keywords: impression technique; occlusal contact; functionally generated path; FGP; occlusal force.

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Introduction

When dental prostheses are delivered to patients, occlusal corrections are usually necessary. In 1975, in his report regarding this extremely unfavorable phenomenon, Douglass asked, “The cast restoration—why is it high?” (1). Loos et al. stated that the long office visit time required for occlusion corrections is a major source of consternation (2). Correcting the prostheses to match the oral function chairside would be an extremely difficult procedure, and expert clinical techniques and experience are required. The occlusal surface, polished completely by dental technicians, would be damaged and would have to be repolished.

Vergos et al. reported that a vertical discrepancy of 0.5 mm occurs regardless of the type of maxillomandibular registration material used (3). To reduce the discrepancy while the casts are mounted on the articulator, double arch impression techniques have traditionally been used in clinical settings (4-10). Wilson et al. reported that the

use of a double arch, closed-mouth technique enables dentists to obtain cast and die placements in centric occlusion in a single step; complete closure of the teeth is mandatory to correctly register the interocclusal relationship (4). However, since impressions easily deform due to the fact that the stock trays used for double arch impressions lack rigidity, there is fear that the impressions will be deformed. There is little evidence regarding the accuracy of double arch impression techniques, including laboratory procedures (11-13).

The clinical question of which type of guidance is better for prosthetic appliances has long been widely discussed. There are many occlusal schemes including canine-protected articulation, group function, mutually protected occlusion, and sequential functional guidance occlusion. To realize the occlusal schemes for prosthetic appliances, the patient's mandibular movement must be accurately reproduced using elaborate articulators. However, it is extremely difficult to handle such articulators; a great deal of experience and practice would be necessary.

In another method, the patient's mandibular movement is recorded as the functional movement path of the opposing teeth without an elaborate articulator. Meyer defined *the functional occlusal path* as "a balanced mutual relationship among occlusion, the cuspal path, the condylar path, and the neuromuscular system" (14,15), and Pankey and Mann modified the "functionally generated path (FGP)" (16). The FGP technique is now widely applied in the construction of complete dentures, fixed prostheses, and implant prostheses (17-23); however, the number of patient visits necessary has increased and laboratory procedures are arduous (20-22).

Suzuki et al. reported the functional bite impression (FBI) technique, which integrates impression under occlusal force, FGP recording, and registration of the maxillomandibular relationship (24,25). This clinical procedure enables the fabrication of prosthetic appliances with little occlusal corrections upon delivery. The FBI technique can be applied to a single restoration or complete dentures, including implant prostheses; however, the only reports regarding the FBI technique have been clinical and there has been no scientific verification.

The present study aimed to experimentally verify the accuracy of the FBI technique as compared with conventional techniques. Typodonts having teeth and soft tissue with precise deformations under occlusal force were prepared and mounted on the semi-adjustable articulator as simulation models. These simulation models measured excessively high occlusion and the occlusal contact area during mandibular lateral movements of metal restorations (restorations) and removable partial dentures (RPDs) fabricated using FBI and conventional techniques.

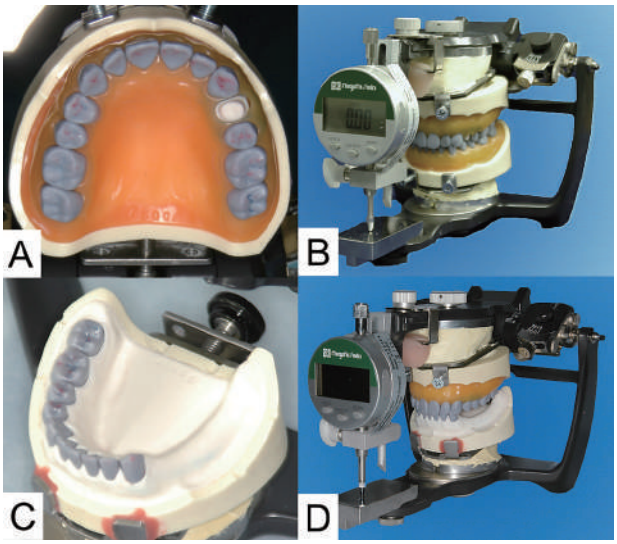

Fig. 1 Simulation models used in the present study. (A) Typodont for restoration. (B) Simulation model for restoration. (C) Typodont for RPD. (D) Simulation model for RPD.

Materials and Methods

Procedures for the FBI technique

In the present study, the FBI technique was performed using the following procedures, similar to those in clinical practice: 1) fabrication of the custom tray with an FGP table (FBI tray); 2) FGP recording; 3) impressions under occlusal force; 4) fabrication of a definitive cast; 5) mounting on the articulator (without removal of the cast from the impression); 6) fabrication of an opposing cast and mounting to the articulator; 7) modification of the opposing cast to a functional occlusal surface; and 8) removal of the impression from the cast.

Procedures for restoration

Each simulation model consisted of a typodont (D18FE-500A-QF, Nissin, Kyoto, Japan) and a semi-adjustable articulator (ProArch IV, Shofu, Kyoto, Japan). To provide physiological displacement under the load, artificial periodontal ligaments were added to the roots of all teeth (A2AN-TUP.66, Nissin) using silicone impression material (0.3 mm thickness; Fit Checker, GC, Tokyo, Japan) (26). The typodont was mounted on the articulator with a Balkwill angle of 21°, a Bonwill triangle of 110 mm × 105 mm × 105 mm, and an 11° angle formed by the occlusal plane and the Frankfort horizontal plane (27-29). The occlusion of the simulation model was adjusted to

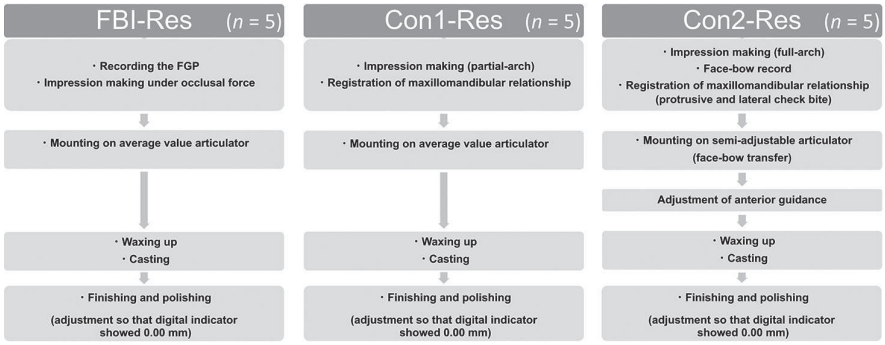

Fig. 2 Flow chart of restoration.

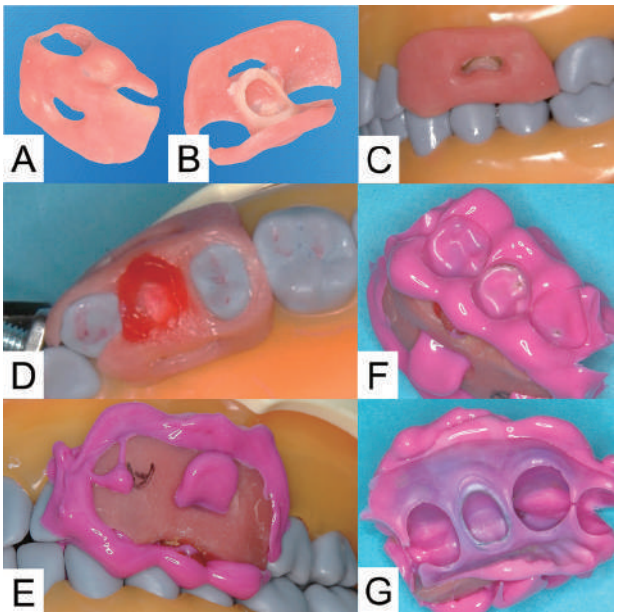

Fig. 3 Clinical procedure of the FBI for restoration. (A, B) FBI tray. (C) Trial and adjustment of the FBI tray. (D) After FGP recording. (E) Double arch impression under occlusal force. (F, G) Completed FBI technique.

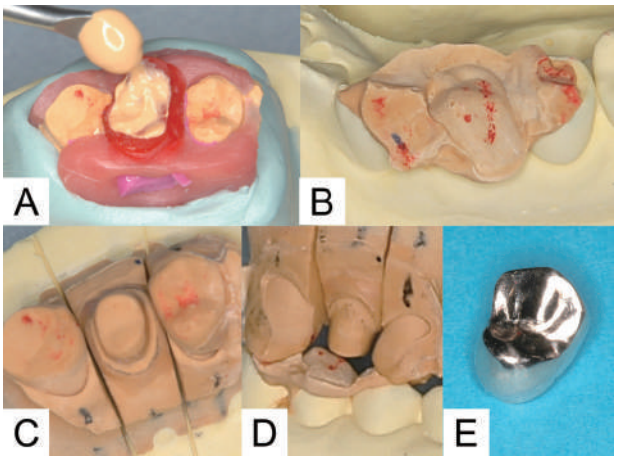

Fig. 4 Laboratory procedure of the FBI for restoration. (A) Produced functional cast. (B) Functional cast of the opposing teeth. (C, D) Definitive cast. (E) Fabricated restoration.

contact all teeth from the canine to the second molar during intercuspation as the group function, involving contact from the canine to the second premolar on the working side during lateral movement. To measure excessively high occlusion at the restoration placement, a digital indicator (accuracy: 10 μm, DEI-127, Niigata Seiki, Niigata, Japan) was mounted on the incisal guide pin of the articulator (Fig. 1A, B).

A maxillary left first premolar was prepared for the restoration. Five impressions were made by each of the following techniques ($n = 5$): 1) FBI technique (FBI-Res); 2) conventional technique 1 (Con1-Res); and 3) conventional technique 2 (Con2-Res) (Fig. 2). For FBI-Res, an FBI tray was fabricated with auto-polymerized resin (Tray Resin II, Shofu) (Fig. 3A-C), and the FGP was recorded using a pattern resin (Pattern Resin, GC) (Fig. 3D); double arch impressions were made using a silicone impression material (Imprint4 Light, 3M, New Ulm, MN, USA) (Fig. 3E-G) under a 1.2-kg load. The casts using the FBI technique were mounted on an average value articulator (Gysi Simplex OU-H3, Comatsu, Saitama, Japan) without removal of the cast from the impression (Fig. 4A-D). For Con1-Res, individual trays for the partial arch and prepared premolar were fabricated with auto-polymerized resins (Tray Resin II, Shofu; and Unifast III, GC, respectively). With two silicone impression materials (Imprint4 Light, for the abutment tooth; Imprint4 Soft tray body, 3M, for the arch), a combination impression was made for the abutment tooth and the adjacent teeth. The maxillomandibular relationship was registered using silicone material (Correct Plus Bite Superfast, Pentron Clinical, Orange, CA, USA) under a 1.2-kg load (12). Definitive and opposing dentition casts were fabricated with dental plaster (New Fujirock, GC),

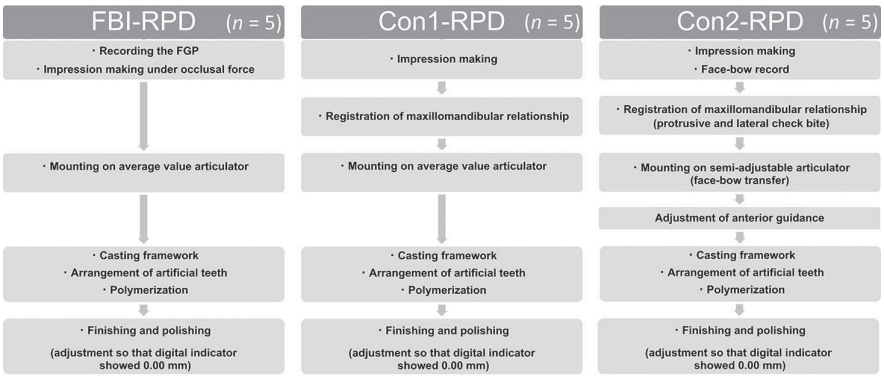

Fig. 5 Flow chart of RPD fabrications.

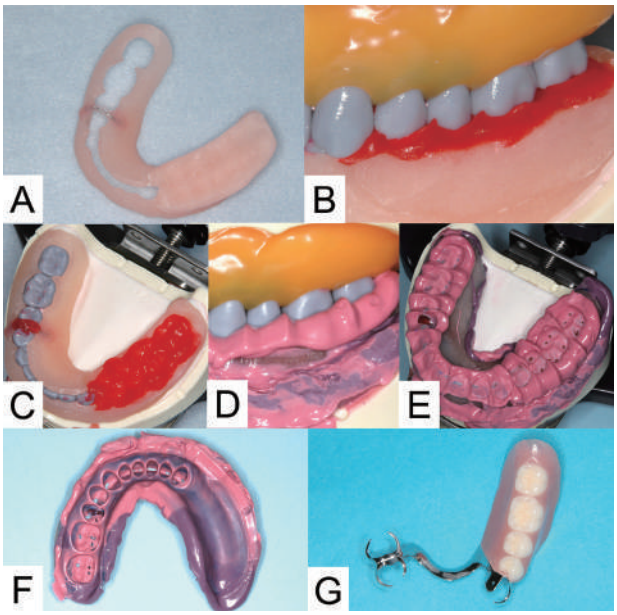

Fig. 6 Procedure of the FBI technique for RPD fabrications. (A) FBI tray. (B, C) FGP recording. (D) Double arch impression under occlusal force. (E, F) After FBI technique. (G) Fabricated RPD.

and were mounted on an average value articulator (Gysi Simplex OU-H3). Full arch combination impressions were made for Con2-Res using the same procedure and materials as Con1-Res. A facebow (Denar Slidematic Facebow, Whip Mix, Louisville, KY, USA) was used to record the three-dimensional positional relationships of the maxillary dentition; silicone material was used for lateral (left and right) and protrusive interocclusal record. The casts were mounted on a semi-adjustable articulator (Denar Multiculator Articulator, Yoshida, Tokyo, Japan), and the condylar path was adjusted in accordance with standard methods.

A digital indicator (DEI-127, Niigata Seiki) was attached to the incisal guide pin of all articulators. All casts were modified as divided dies, and wax patterns were made in the standard manner. After all wax patterns were invested into cristobalite (Cristobalite Q, Dentsply Sirona K.K., Tokyo, Japan), they were cast with a type IV gold ally (PGA-3, Ishifuku Metal Industry, Tokyo, Japan), and finished and polished according to the manufacturer's instructions. The occlusal height of restorations was adjusted such that the digital indicator showed 0 μm in the intercuspal position, and the group function during lateral movements was confirmed (Fig. 4E). All clinical and laboratory procedures for fabricating restorations were performed by a single dentist.

Procedures for RPD fabrication

Similar to restorations, RPDs were fabricated using a simulation model. The occlusion of the typodont was adjusted such that the left and right canines and the first premolars were in contact during lateral movement. From the mandibular left first premolar to the second molar, the tooth model was removed from the typodont, and its extraction socket was sealed with a defect plug (A2A-565, Nissin) and formed to a residual ridge. Not only periodontal ligaments, but also artificial soft tissues, were made from silicone impression material (Fit Checker) at a thickness of 2.0 mm on the partially edentulous residual ridge (26). After the simulation model was readied, rest seats were prepared at the distal aspect of the mandibular right first premolar, the proximal aspect of the second premolar, and the cingulum aspect of the mandibular left canine in the typodont (Fig. 1C, D).

Five impressions were made by each of the following techniques (n = 5): 1) FBI technique (FBI-RPD); 2) conventional technique 1 (Con1-RPD); and 3) conventional technique 2 (Con2-RPD) (Fig. 5). For FBI-RPD, the FGP was recorded (Fig. 6B, C) using an FBI tray (Fig. 6A), and double arch impressions were made using two silicone impression materials (Fusion II Monophase Type, GC; Fusion II Wash Type, GC; Fig. 6D-F) under a 1.2-kg load. For Con1-RPD and Con2-RPD, selective pressure impressions were made using individual trays

with silicone impression materials (Fusion II Monophase Type; Fusion II Wash Type). Dental plaster (New Fujirock) was poured into the impressions; definitive casts and opposing dentition casts were fabricated. The maxillomandibular relationship was registered for Con1-RPD and Con2-RPD using an occlusion rim under a 1.2-kg load (12). In all procedures, casts were mounted on the articulators in a manner similar to that for restorations.

A RPD framework was designed with a computer-aided design (CAD) system by scanning a definitive cast with an extraoral digital scanner (D2000, 3Shape, Copenhagen, Denmark) and using denture design software (Partial Design Module, 3Shape). Wax patterns of the designed framework were cut using a dental milling machine (DWX-51D, Roland DG, Shizuoka, Japan), invested to phosphate-bonded material (Heravest M, Kulzer, Hanau, Germany), and cast with a Co-Cr alloy (Remanium GM 380+, Dentaurum, Ispringen, Germany); finishing and polishing were performed in accordance with the manufacturer's instructions. After the hardened resin denture teeth (Livdent Grace AS-33M, GC) were arranged, wax dentures were invested and polymerized with an acrylic resin (PalaXpress, Kulzer). The completed RPDs on the definitive casts were remounted on the articulator, and the RPDs were adjusted for the following factors: 1) a digital indicator displaying 0 μm in the intercuspal position; 2) equal contact of the canine and the first premolar during lateral movements; and 3) the absence of contact of the second premolar and first and second molars during lateral movement (Fig. 6G). With the exception of the framework, all clinical and laboratory procedures for RPD fabrications were completed by a single dentist.

Measurement of occlusion accuracy

Three impression and maxillomandibular registration techniques for restorations and RPDs were assessed by measuring excessively high occlusion and the occlusal contact area during lateral movement. The lifted stylus of a digital indicator was measured in the intercuspal position, when restorations and RPDs were placed on the simulation model to determine the excessively high occlusion. The areas of occlusal contact during lateral movement were recorded in a 1-mm leftward position using a silicone material (Blue silicone low flow, GC) and an occlusal analytical device (BiteEye BE-I, GC) (30). The guidance of the restoration was assessed by the sum of the occlusal contact area from the mandibular left canine to the second premolar. The guidance of the RPDs was assessed by the difference in the occlusal contact area on the mandibular left canine prior to and following placement of the RPD and the occlusal contact area of the mandibular left first and second premolars following placement of the RPD. In the present study, silicone material thicker than 30 μm was defined as occlusal contact (30) (Fig. 7).

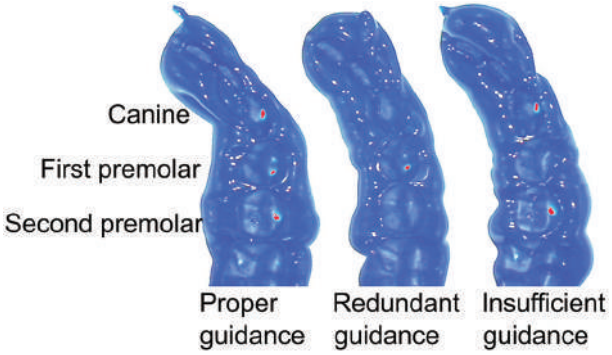

Fig. 7 Assessment of occlusal contacts for guidance during lateral movement using silicone registration material. The red regions indicate occlusal contact areas (thickness <30 μm).

Statistical analysis

In excessively high occlusion and occlusal contacts during lateral movement, Kruskal-Wallis and Steel-Dwass tests were executed with a significance level of 5%. All statistical analyses were performed with EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), a graphical user interface for R 2.13.0 (R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria) (31). Results are presented as the median (IQR).

Results

Excessively high occlusion

We used silicon material and confirmed that there were no restorations with low occlusion in any group. Con1-Res, Con2-Res, and FBI-Res showed excessively high occlusions of 120 (80-140) μm, 70 (70-130) μm, and 10 (10-20) μm, respectively, in the intercuspal position. There were significant differences between FBI-Res and Con1-Res and between FBI-Res and Con2-Res ($P < 0.05$). No significant difference was found between Con1-Res and Con2-Res ($P \geq 0.05$; Fig. 8A).

Similarly, the excessively high occlusions of Con1-RPD, Con2-RPD, and FBI-RPD were 170 (120-220) μm, 190 (140-280) μm, and 30 (10-40) μm, respectively. Although there were significant differences between FBI-RPD and Con1-RPD and FBI-RPD and Con2-RPD ($P < 0.05$), no significant difference was observed between Con1-RPD and Con2-RPD ($P \geq 0.05$; Fig. 8B).

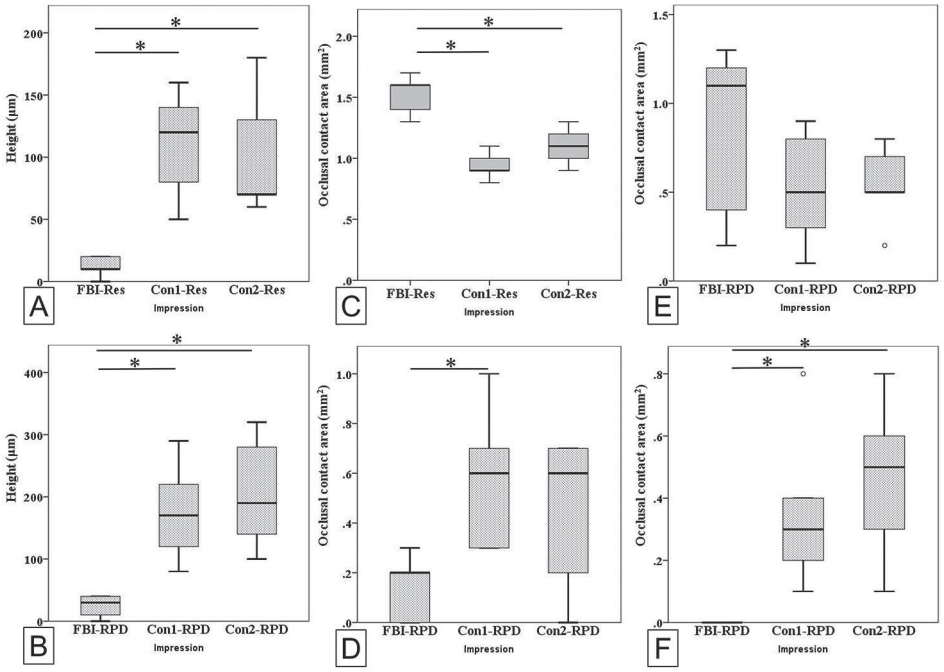

Fig. 8 Results of occlusion accuracy. (A) Amounts of excessively high occlusion (restorations). (B) Amounts of excessively high occlusion (RPDs). (C) Guidance (restorations, sum of occlusal contact areas; the mandibular left canine to the second premolar). (D) Guidance (RPDs, the differences in occlusal contact areas; the mandibular left canine prior to and following RPD placement). (E) Guidance (RPDs, the occlusal contact area; the mandibular left first premolar). (F) Guidance (RPDs, the occlusal contact area; the mandibular left second premolar) ($n = 5$, $*P < 0.05$).

Occlusal contacts during lateral movement

During a 1-mm lateral movement, FBI-Res showed significantly greater contact areas than Con1-Res or Con2-Res ($P < 0.05$). Moreover, the contact areas of FBI-Res were approximately one and half times higher than those of Con1-Res and Con2-Res during a 1-mm lateral movement ($P < 0.05$). There was no significant difference between Con1-Res and Con2-Res ($P \geq 0.05$; Fig. 8C).

With respect to RPDs, the difference in the contact area of FBI-RPD was the lowest among all techniques during 1-mm lateral movements. Although the occlusal contact area on the mandibular left first premolar of FBI-RPD was the highest, the second premolar was the lowest during 1-mm lateral movements. A Steel-Dwass test revealed significant differences in the occlusal contact areas on the mandibular left canine prior to and following RPD placement of FBI-RPD and Con1-RPD ($P < 0.05$; Fig. 8D). On the mandibular left second premolar, there were significant differences between FBI-RPD and Con1-RPD and between FBI-RPD and Con2-RPD ($P < 0.05$; Fig. 8F). No significant differences were found on the mandibular left first premolar among any techniques ($P \geq 0.05$; Fig. 8E).

Discussion

The FBI technique has two main objectives; recording the FGP of opposing teeth and impression of the soft tissues and teeth under occlusal force. To evaluate the accuracy of the FBI technique, the mandibular movements and the pressure displacement of teeth and soft tissues in the simulation model had to reproduce as closely as possible those of living patients. Previously, the displacements of teeth and soft tissue have been reported as 30-120 μm and 300 μm, respectively (32-34). In accordance with the methods described by Kono et al. silicone impression material was used for artificial soft tissues (2.0-mm thickness) and periodontal ligaments (0.3-mm thickness) (26,32-34). Prior to the experiments, approximately 30 μm dentition displacement was confirmed under a 1.2-kg load. In the present study, the ProArch IV was selected since it has a centric lock mechanism, the condylar path on the working side can be adjusted, and the immediate and progressive mandibular lateral translation can be registered.

A small impression area would be better for the following reasons: 1) minimization of the shrinkage of impression materials and the expansion of cast materials; 2) decreased burden on the patients; and 3) reduced cost. Therefore, partial arch or several teeth impressions

may be preferable for the fabrication of single restorations. However, maxillary and mandibular partial arch definitive casts are unstable in the intercuspal position, and the condylar path cannot be adjusted when the restoration is mounted on an adjustable articulator. Since the restorations required proper contact for guidance in the present study, full arch impressions were made, and the maxillary and mandibular casts were mounted on a semi-adjustable articulator. With the conventional techniques, individual trays for the abutment tooth were used to facilitate excellent dimensional accuracy and to prevent deformation due to undercuts of adjacent teeth. FBI also used individual trays for the abutment tooth. The accuracy of the tooth die must be similar among Con1-Res, Con2-Res, and FBI-Res. Of the RPDs, full arch selective pressure impressions were made using all techniques. However, Con1-RPD and Con2-RPD were made under hand pressure, but FBI-RPD used occlusal force according to clinical situations. Thus, there will be slight differences in definitive casts between conventional and FBI techniques, especially regarding the shape of soft tissues.

Excessively high occlusion was measured using a micrometer attached to the incisal guide pin of the simulation model. The hinge movement was performed with the condyle as the axis in the simulation model; therefore, the excessive high occlusion values were approximately double the actual amount. Accordingly, the actual excessive high occlusions of the restorations and RPDs using the conventional techniques were approximately 50 μm and 100 μm, respectively. In the present study, better accuracy could be obtained than that seen in clinical practice (3,35). The guidance was assessed by the occlusal contact area during lateral movement using the silicone registration material (30). Based on a report by Komiyama et al. the existence of occlusal contact was defined by a silicone thickness <30 μm (9). Lateral guidance on the simulation model for restoration was adjusted such that the canine and second premolar exhibited a gliding movement. When the restoration (first premolar) matched well with the guidance, many contacts were obtained on the canine and second premolar during lateral movement; thus, the sum of the occlusal contact area, including the first premolar, was increased. Conversely, only contact on the first premolar was shown when the guidance was redundant on the placed restoration; additionally, contact was obtained only on the canine and second premolar when the guidance on the placed restoration was insufficient. Consequently, the sum of the occlusal contact area was decreased as compared with proper guidance (Fig. 7). Therefore, the lateral guidance of the restoration could be assessed by the sum of the occlusal contact areas of the placed restoration and both adjacent teeth. Similarly, the RPD guidance assessed the contact of the canine and the denture teeth (first and second premolars). The RPDs were adjusted such that contact was made on the canine and first premolar, while the second premolar was open. When there was redundant guidance on the RPDs, the occlusal contact area of the canine was decreased as compared with that prior to RPD placement; it was increased on the first and second premolars. Conversely, the occlusal contact area of the canine did not change when there was insufficient guidance of the RPDs, and it was decreased or absent on the first and second premolars. The guidance accuracy of RPDs could be assessed by changes in the occlusal contact.

Generally, the occlusions of the completed prostheses are remarkably higher when delivered to the mouth. Hasegawa et al. reported that the amount of excessive high occlusion was 200-300 μm (35). The height of a prosthesis is affected by problems arising from the materials (i.e., shrinkage of the impression materials and expansion of the plasters) and the patient (i.e., changes in the shape of dental arch during the impression and tooth displacement due to occlusal force). When patients must open their mouths widely during impression, the mandibular arch is deformed (36,37). Although teeth are depressed by approximately 30 μm upon light occlusion in the intercuspal position, the normal impression cannot record the tooth displacement. These deformities and displacements cannot be replicated precisely in a definitive cast. The merit of the FBI technique is that the maxillary and mandibular casts can be mounted onto an articulator without removal of the impression from the cast. For this reason, appropriate three-dimensional positional relationships of maxillary and mandibular casts in the intercuspal position can be reproduced on an articulator. In the present study, the conventional techniques yielded prostheses with higher occlusion, whereas the FBI technique involving impression under guidance exhibited more accurate occlusion, which is consistent with previous clinical studies (6-8). Even though a single operator repeatedly fabricated prostheses using the same devices for all techniques, the amounts of excessive high occlusion varied greatly between the conventional techniques, but the FBI technique resulted in much smaller variations. Since the FBI technique enables an accurate maxillomandibular positional relationship, prostheses can be largely reproduced, and few occlusal corrections are necessary upon delivery to the mouth.

With 1-mm lateral movements, the FBI technique yielded restorations with greater contact areas than

those fabricated using conventional techniques. Con1 and 2-Res lacked contacts for proper guidance, meaning that there was only guidance on the canine and second premolar, or there was only strong guidance by the first premolar of the placed restoration. In contrast, FBI-Res maintained the original proper occlusal contacts for guidance on the canine and second premolar, and appropriate new occlusal contacts for guidance were additionally obtained on the first premolar. In FBI-RPD, the differences in the contact area on the canine prior to and following denture placement were significantly smaller as compared with those in Con1-RPD. The redundant guidance in Con1-RPD may have reduced the original guidance on the canine, thereby increasing the difference in occlusal contact area prior to and following the placement of RPDs. Conversely, FBI-RPD maintained the original guidance of the canine, which may have decreased the differences in the occlusal contact area. While the RPDs were fabricated without guidance on the second premolar, Con1- and 2-RPD created new contacts on the second premolar during lateral movement. In both restorations and RPDs, redundant guidance was observed with conventional techniques, which may be the result of differences in the condylar path angles between the typodont and the articulators. Since the FBI technique records the FGP, prostheses that are well matched to the characteristics of mandibular movement can be constructed (20,22,23). From the above results, the FBI technique can be recommended for the fabrication of highly accurate prostheses that are well matched to oral function with the intended guidance. However, the mandibular movement was not curved, and mandibular deformation was not reproduced during mouth opening in simulation models consisting of a typodont or an articulator as in the present study. Further *in vivo* assessments are necessary to clarify precise prostheses using the FBI technique.

To evaluate the clinical effectiveness of the FBI technique, the excessively high occlusion and occlusal contact area during lateral movement of a single restoration (first premolar) and unilateral extension base RPDs (four missing teeth) fabricated using FBI and conventional techniques were measured on a simulation model including a typodont with artificial periodontal ligaments and soft tissue. Within the limitations of the present study, the following conclusions can be made:

1. Restorations and RPDs fabricated by partial arch and full arch conventional impressions using average value or semi-adjustable articulators yielded higher occlusions (restorations, approximately 100 μm; RPDs, approximately 200 μm).

2. Excessive occlusal contacts for guidance were observed during lateral movement on restorations fabricated using conventional techniques.

3. Conventional techniques produced redundant guidance on the RPDs during lateral movement.

4. The FBI technique provided the proper height of occlusion in the intercuspal position and appropriate occlusal contacts for guidance in both restorations and RPDs during lateral movement.

These conclusions suggest that the FBI technique makes effective impressions, and the maxillomandibular registration method of fabricating highly accurate prostheses matches well with oral function.

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Conflict of interest

The authors declare that they have no conflict of interest regarding this work.

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