THE JOURNAL OF PROSTHETIC DENTISTRY

CLINICAL RESEARCH

Design of wear facets of mandibular first molar crowns by using patient-specific motion with an intraoral scanner: A clinical study

Linlin Li, BDS,[a] Hu Chen, DDS, PhD,[b] Weiwei Li, PhD,[c] Yong Wang, MS, SCI,[d] and Yuchun Sun, DDS, PhD[e]

ABSTRACT

Statement of problem. Although computer-aided design has become popular, restorations are typically designed from static occlusion and dynamically by using an average-value virtual articulator. Patient-specific motion recorded by using an intraoral scanner has rarely been used to design restorations, and its design ability has not been analyzed.

Purpose. The purpose of this clinical study was to record patient-specific motion by using an intraoral scanner and to analyze its ability to design the morphology of the wear facets on mandibular first molar crowns.

Material and methods. An intraoral scanner was used to scan complete arch digital casts and to record patient-specific motion of 11 participants. Right and left mandibular first molars were selected as the target teeth. The complete crown preparations of the target teeth were virtually prepared on the digital mandibular casts by using the Geomagic Studio 2013 software program. High points were created by elevating the wear facets of the target teeth by 0.3 mm in the occlusal direction to generate digital wax patterns. The Dental System software program was used to design crowns with the anatomic coping design method. Occlusal adjustment with static occlusion (STA crown), with the average-value virtual articulator (DYN crown), and with patient-specific motion (FUN crown) was carried out. The crowns adjusted with these 3 methods were compared with the original wear facets. The mean value and root mean square (RMS) of 3D deviation were measured. One-way ANOVA was used to analyze the influence of the occlusal surface design methods on the morphology of the wear facets (α=.05).

Results. The STA crowns had the poorest results with the mean ±standard deviation 3D deviation value of 0.15 ±0.05 mm and RMS value of 0.19 ±0.04 mm. The best results occurred in the FUN group, with the mean ±standard deviation 3D deviation value of 0.05 ±0.06 mm and RMS value of 0.13 ±0.03 mm. Significant differences were found among the 3 groups (P<.01). Except for the RMS value between the STA and DYN groups, significant differences were found between groups from the pairwise comparisons.

Conclusions. The occlusal surface of the crowns designed by using the patient-specific motion recorded with the intraoral scanner had the best coincidence with the morphology of the wear facets on the original teeth. (J Prosthet Dent 2021;■:■-■)

L.L. and H.C. contributed equally to this work. Supported by the National Natural Science Foundation of China (grant numbers 52035001); National Key R&D Program of China (grant numbers 2019YFB1706900); Capital Science and Technology Leading Talent Project (grant numbers Z191100006119022).

[a]Doctoral student, Faculty of Prosthodontics, Center of Digital Dentistry, Peking University School and Hospital of Stomatology & National Engineering Laboratory for Digital and Material Technology of Stomatology & Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health & Beijing Key Laboratory of Digital Stomatology, National Clinical Research Center for Oral Diseases, Beijing, PR China.

[b]Attending Doctor, Faculty of Prosthodontics, Center of Digital Dentistry, Peking University School and Hospital of Stomatology & National Engineering Laboratory for Digital and Material Technology of Stomatology & Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health & Beijing Key Laboratory of Digital Stomatology, National Clinical Research Center for Oral Diseases, Beijing, PR China.

[c]Postdoctoral, Faculty of Prosthodontics, Center of Digital Dentistry, Peking University School and Hospital of Stomatology & National Engineering Laboratory for Digital and Material Technology of Stomatology & Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health & Beijing Key Laboratory of Digital Stomatology, National Clinical Research Center for Oral Diseases, Beijing, PR China.

[d]Professor, Faculty of Prosthodontics, Center of Digital Dentistry, Peking University School and Hospital of Stomatology & National Engineering Laboratory for Digital and Material Technology of Stomatology & Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health & Beijing Key Laboratory of Digital Stomatology, National Clinical Research Center for Oral Diseases, Beijing, PR China.

[e]Professor, Faculty of Prosthodontics, Center of Digital Dentistry, Peking University School and Hospital of Stomatology & National Engineering Laboratory for Digital and Material Technology of Stomatology & Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health & Beijing Key Laboratory of Digital Stomatology, National Clinical Research Center for Oral Diseases, Beijing, PR China.

Clinical Implications

Patient-specific motion can be recorded by using the TRIOS intraoral scanner and integrated into the restoration design process without the need of additional equipment or procedures. The patient-specific motion function may improve the occlusal morphology of complete crowns and reduce clinical adjustment.

The occlusion and occlusal surfaces of dental restorations contribute to static and dynamic occlusion,[1] and tooth excursions, as well as the intercuspal position, should be replicated[2] so that restorations do not cause interferences in dynamic occlusion.[3] In the conventional workflow, the quality of a restoration is associated with the skill of the dentist and the dental laboratory technician and the physical property of the materials.[4,5] With a fully digitized workflow using the computer-aided design and computer-aided manufacturing (CAD-CAM) technology,[6] intraoral scanners (IOSs) provide precise 3-dimensional (3D) information of the prepared tooth, adjacent teeth, and antagonist teeth which are used for the virtual design of the restoration.[7] Digital scanning can optimize workflow efficiency, improve patient comfort, reduce laboratory and clinical treatment times, simplify laboratory production, and improve communication between the dentist and the dental laboratory technician.[8-10] In addition, crowns fabricated with a digital workflow have been reported to have better marginal fit, proximal contact, occlusal contact, and crown morphology.[4,10-13] With the digital workflow, less experienced clinicians and dental laboratory technicians should be able to provide restorations of a quality similar to that produced by experts.[11]

The occlusal surface of CAD-CAM crowns is typically generated by the CAD software program based on standard morphology and may require occlusal adjustment.[14-17] With improvements in CAD software programs, algorithms can be used to fit the occlusal surface to static and dynamic occlusions such as the biogeneric tooth model. This mathematical algorithm gathers information from the morphology of the remaining teeth and occlusal relationship to generate a natural occlusal surface consistent with that of the adjacent teeth.[18,19] The method of mirroring allows the operator to copy the contralateral tooth and create a mirror image on the preparation.[20,21] The biogeneric copy design mode can replicate the dental morphology of existing teeth, diagnostic wax patterns, and interim designs.[22-26]

Digital functional generated path (FGP) registration and virtual articulators have been introduced to design restorations dynamically. The FGP technique eliminates the need to reproduce mandibular movements on the articulator and reduces time for intraoral occlusal adjustment.[27] However, the method is highly technique sensitive and errors can be introduced by distortion of the recording materials used.[28,29] The virtual articulator deals primarily with functional aspects of occlusion[30,31] and can simulate mandibular movement in the digital environment with both average settings and individual information to help design restorations dynamically. Different mandibular movement recording systems can be used to record individual mandibular movement and to program a virtual articulator.[32] However, recording mandibular movement is time-consuming and requires dentists to be skilled in the use of various software programs and equipment. Therefore, in clinical practice, information about individual mandibular movement is rarely used to design the occlusal surfaces of restorations. Digital casts are frequently mounted on a virtual articulator set with average values and default articulator settings, possibly leading to design errors.

The effect of different residual dentitions on the dynamic adjustment of the wear facet morphology on mandibular first molar crowns has been evaluated with an average-value virtual articulator, concluding that average-value articulation cannot represent individual mandibular movement, especially when there were insufficient residual reference teeth to constrain the path.[33] Restorations designed by using individual mandibular movement have been reported to be better matched to the morphology of the wear facets on the original teeth than those designed by using an average-value virtual articulator.[34] However, using individual mandibular movement caused negative errors for the recording, registration, and simulation. Theoretically, recording tooth-guided protrusive and laterotrusive movements could provide information to create the morphology of the occlusal surfaces of the restorations to eliminate occlusal interferences, providing occlusal surfaces in balance with the masticatory muscles.[35] However, recording individual mandibular movement and designing restorations with the recorded movement should be straightforward and accurate.

The TRIOS 3 and TRIOS 4 (3Shape A/S) IOSs include the patient-specific motion (PSM) function to record dynamic occlusion along with the acquisition of 3D dentition data. Valenti and Schmitz[36] described the clinical process of designing restorations with PSM. Dental occlusion and PSM are captured by scanning the interim restorations in static and dynamic occlusions. The technique took advantage of the preoperative scan and the PSM recording that provides individual dynamic occlusion in eccentric movement. However, Valenti and Schmitz[36] did not report an evaluation of the accuracy of crowns designed with the function. Lee et al[37] reported that PSM demonstrated a reduced occlusal error of single

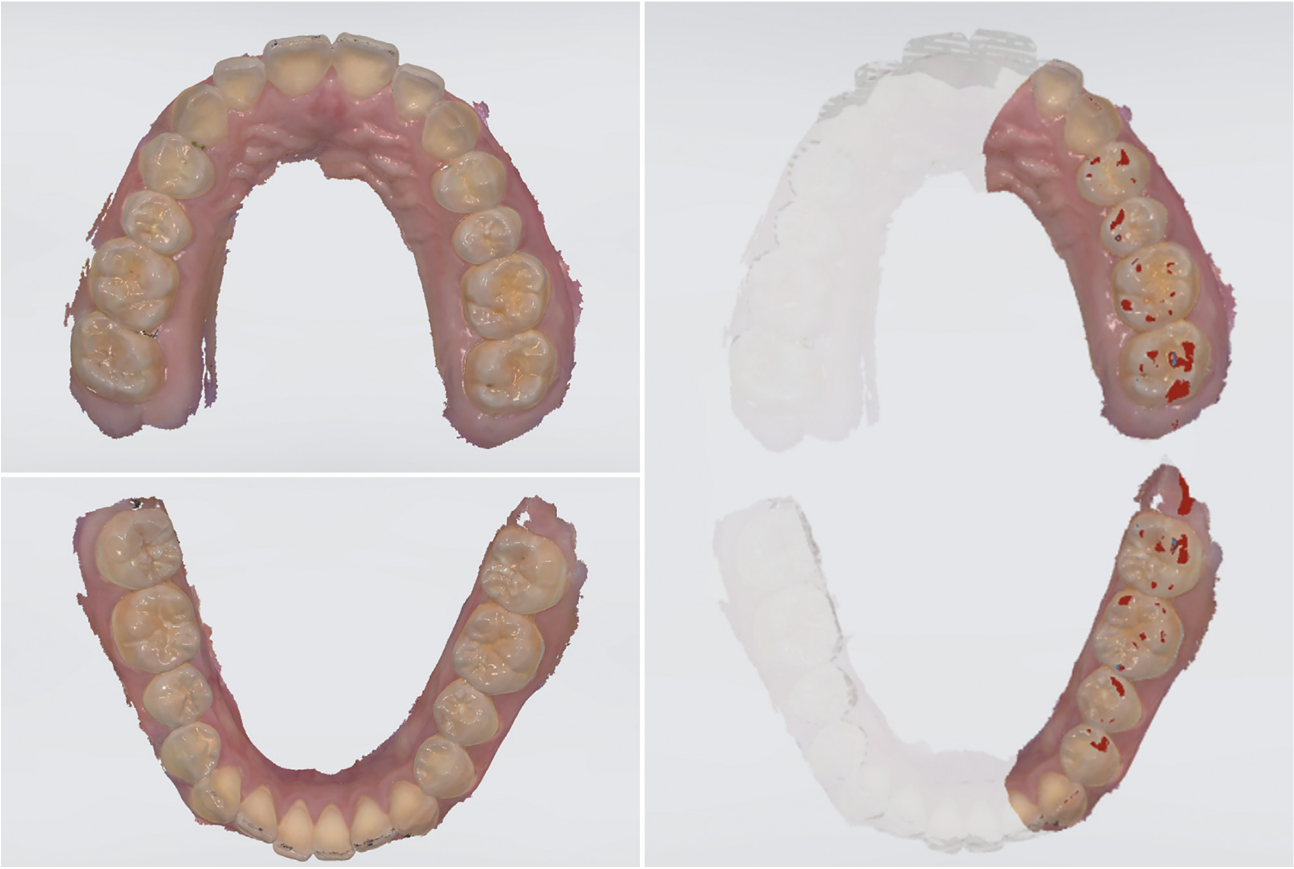

Figure 1. Complete arch digital casts and dynamic occlusal contacts.

posterior crowns compared with static occlusion. However, the operator still needs to scan the digital casts twice and align the casts by using best-fit alignment function, resulting in scanning and registration errors. When the CAD data are compared with the milled data and the milled restoration, errors are unavoidable, causing negative deviation in the occlusal groove.

The purpose of this clinical study was to analyze the ability of the PSM function to design the morphology of the wear facets of mandibular first molar crowns. The null hypothesis was that the morphology of the wear facets designed by using static occlusion, an average-value virtual articulator, and PSM would be similar.

MATERIAL AND METHODS

This clinical study was approved by the Bioethics Committee of the Peking University School and Hospital of Stomatology, PR China (no. PKUSSIRB-201951170). All participants provided informed consent. Inclusion criteria required participants to have a complete permanent dentition, intact occlusal surfaces, sound periodontal tissues, and no signs of temporomandibular disorder. Those with erosion, parafunctional habits, occlusal interferences, high tooth mobility, low occlusal-gingival tooth height, and malocclusion such as reverse articulation and Angle class II or III were excluded. Eleven participants (8 women and 3 men aged from 23 to 29 years and with an average age of 25.3 years) from the Peking University School and Hospital of Stomatology were recruited. Sample size calculation was based on the mean 3D deviation values of the pilot results by using 1-way analysis of variance (ANOVA). The calculated sample size was 10, based on the calculated effect size of 0.62, Type I error at α=.05, and Type II error at 1-β=.80.

The right and left mandibular first molars of the participants were selected as the target teeth. After calibration according to the manufacturer's instructions, an IOS (TRIOS 4 v20.1.2; 3Shape A/S) was used to obtain complete-arch digital casts and buccal occlusion with the recommended strategy. The protrusive and laterotrusive movements were recorded by placing the wand tip at the buccal side of the left first molars and their adjacent teeth (Fig. 1). The digital casts were saved in standard tessellation language (STL) file format, and the order was saved in the 3Shape Order Exchange (3OXZ) file format. The PSM on the right side was recorded and saved similarly. Therefore, 11 pairs of complete-arch casts and 22 dynamic occlusal relationships were obtained. The digital casts were imported into a 3D data-processing

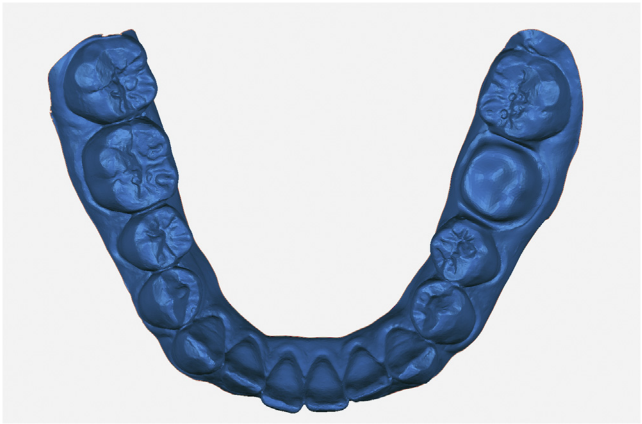

Figure 2. Complete crown preparation.

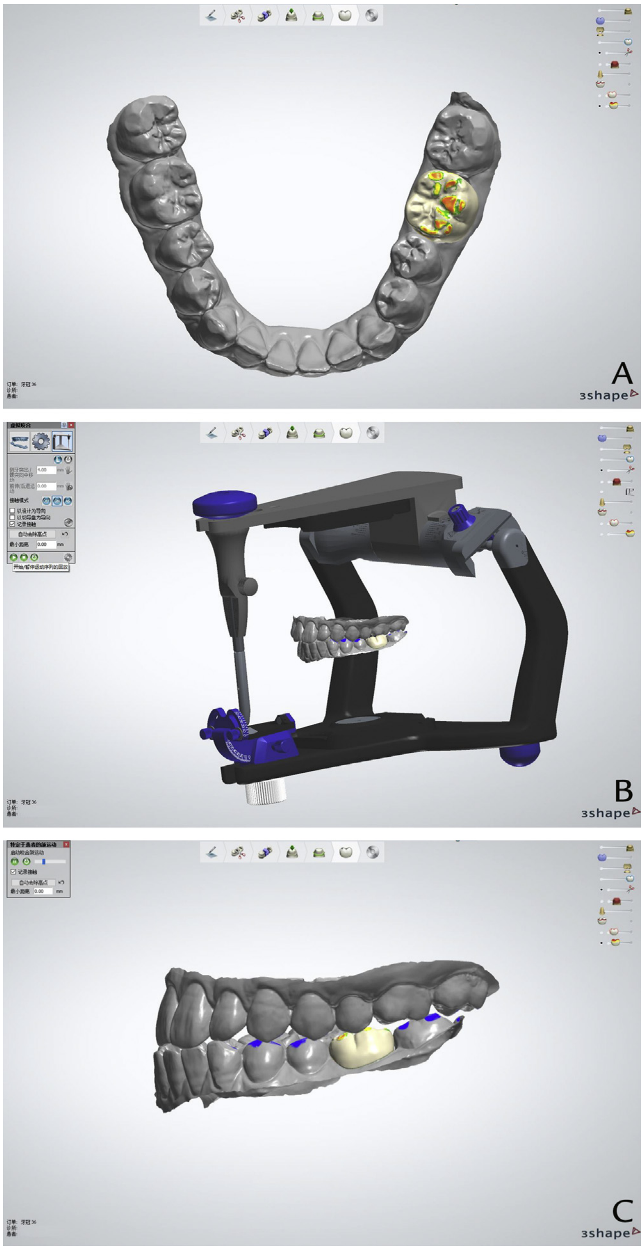

Figure 3. Crowns adjusted by 3 methods. A, Crown adjusted by static occlusion. B, Crown adjusted by virtual articulator with default parameters. C, Crown adjusted by patient-specific motion. *Blue* region on mandibular cast indicates occlusal contacts of dynamic occlusion.

software program (Geomagic Studio 2013; 3D Systems Inc).

The left mandibular first molar was virtually prepared for a complete crown preparation by using the "Sculpt Knife" tool and with the following parameters: occlusal reduction of 1.5 mm, axial reduction of 1 mm, and supragingival chamfer preparation of 1 mm in depth (Fig. 2). The digital cast with preparation was saved as the definitive cast. The wear facets of the left mandibular first molar were selected, and a digital wax pattern was made by elevating the wear facets by 0.3 mm in the occlusal direction.[33] The whole order with PSM on the left side in 3OXZ file format was imported into a CAD software program (Dental System v2019; 3Shape A/S) and modified to design the complete crown of the left mandibular first molar in anatomic coping design mode. The definitive cast, wax pattern, and maxillary cast were then imported into the software program according to the instructions, and the crown surface was generated by copying the morphology of the digital wax pattern. The occlusal interferences detected by the antagonist teeth under static occlusion were eliminated, and the crown was visually outputted as the "static" (STA) crown in STL file format (Fig. 3A). The order in which the design of the STA crown was finished was duplicated twice. One of the 2 duplicated orders was used to design the crown dynamically with an average-value virtual articulator (Virtual Artex CR). The position of the maxillary cast on the virtual articulator was determined automatically and corrected manually for average-value articulation. The parameters of the virtual articulator were set as follows: Bennett angle=10 degrees, inclination of laterotrusive condylar guidance=30 degrees, immediate side shift=0.5 mm, and height of incisal guide pin=0 mm. The morphology of the crown was automatically adapted to the antagonists during the protrusive and laterotrusive movements simulated by the average-value virtual articulator for the "dynamic" (DYN) crown (Fig. 3B). The other duplicated order was used to design the crown dynamically with the PSM recorded by using the IOS, and the morphology was adapted to the PSM for the "functional" (FUN) crown (Fig. 3C).

For the right mandibular first molars, the preparations and digital wax patterns were generated, and the 3 types of crowns were designed in the same way. The 3D deviation between the crown surfaces designed by using the 3 methods and the original morphology of the wear facets was analyzed by using the Geomagic Studio 2013 software program, and the mean value and root mean square (RMS) were calculated.

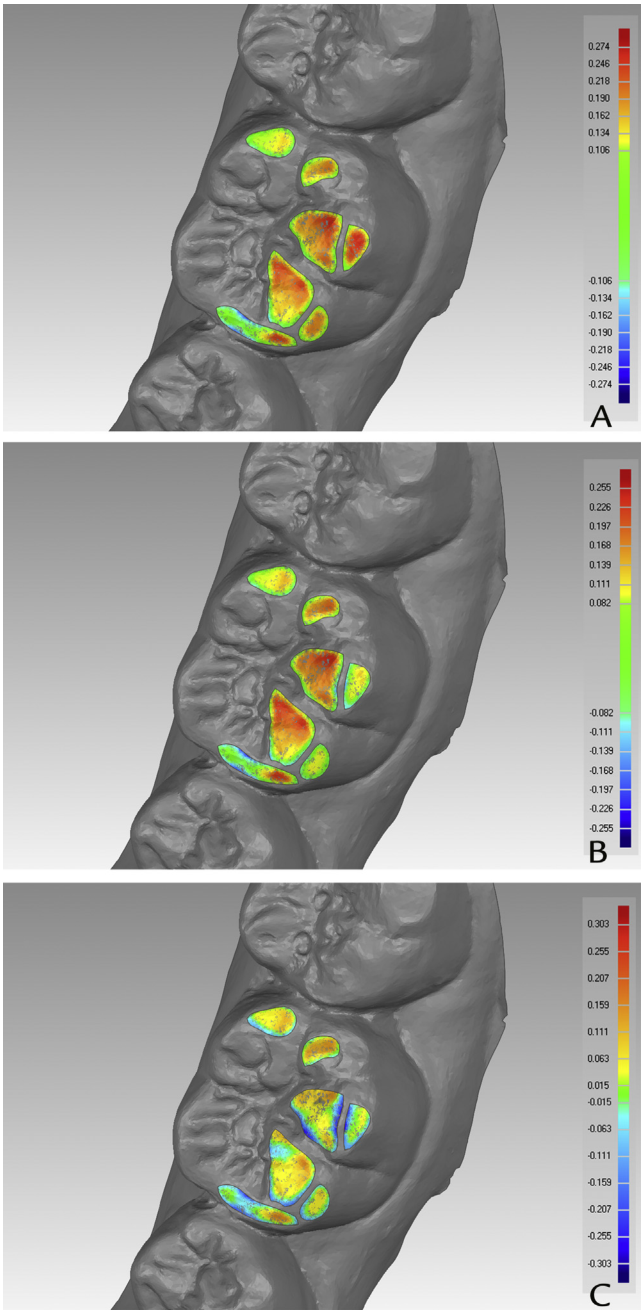

Figure 4. Three-dimensional deviation of 3 groups of crowns. A, STA. B, DYN. C, FUN. DYN, crown adjusted by virtual articulator with default parameters; FUN, crown adjusted by patient-specific motion; STA, crown adjusted by static occlusion.

The Shapiro-Wilk test for normality and the Levene test for equality of variances were used. One-way analysis of variance (ANOVA) followed by the post hoc least significant difference (LSD) test or Kruskal-Wallis test was used for statistical analysis depending on the normality. A statistical software program (IBM SPSS Statistics, v19.0; IBM Corp) was used for all statistical analyses (α=.05).

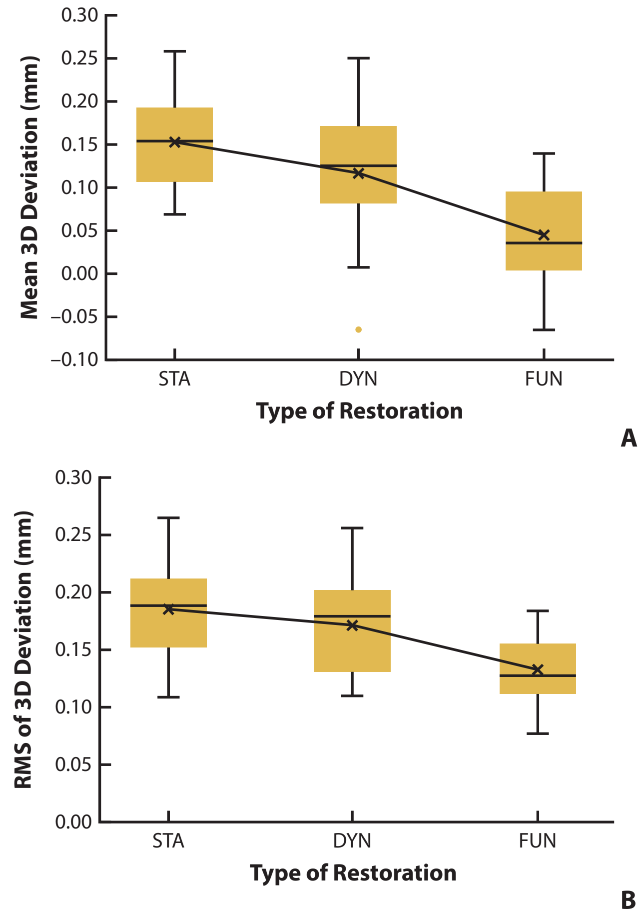

Figure 5. Three-dimensional deviation. A, Mean value. B, RMS value. DYN, crowns adjusted by virtual articulator with default parameters; FUN, crowns adjusted by patient-specific motion; RMS, root mean square; STA, crowns adjusted by static occlusion.

RESULTS

The results of 3D deviation of the crowns designed by the 3 methods are shown in Figures 4, 5, and Table 1. The results were normally distributed (P>.05) with homogeneous variance (P=.129 and P=.551), and 1-way ANOVA was used for the statistical analysis. Significant differences were found among the 3 groups (P<.01). Except for the RMS value between the STA and DYN groups, significant differences were found between groups with the post hoc LSD test (Table 2). The results of the FUN group were lower than those of the STA and DYN groups.

DISCUSSION

The null hypothesis was rejected as the occlusal surfaces designed by using the PSM function had increased coincidence with the morphology of the wear facets on the original teeth. In this clinical study, the TRIOS 4 IOS was used to record the individual mandibular movements without the need of additional equipment or procedures.

Table 1. Results of 3D deviation of crowns adjusted by 3 methods (N=22, mm)

Index		Mean	SD	Min	Max
Mean value	STA	0.15	0.05	0.07	0.26
	DYN	0.12	0.07	-0.07	0.25
	FUN	0.05	0.06	-0.07	0.14
	F	17.860	–	–	–
	P^a	<.001[b]	–	–	–
RMS value	STA	0.19	0.04	0.11	0.27
	DYN	0.17	0.04	0.11	0.26
	FUN	0.13	0.03	0.08	0.18
	F	11.596	–	–	–
	P^a	.001[b]	–	–	–

DYN, crown adjusted by virtual articulator with default parameters; FUN, crown adjusted by patient-specific motion; SD, standard deviation; STA, crown adjusted by static occlusion. [a]One-way ANOVA. [b]Mean difference significant ($P<.05$).

Table 2. Significant difference among groups (mm)

Index	Sample 1 (I)	Sample 2 (J)	Mean Difference (I-J)	Std. Error	P^a
Mean value	STA	DYN	0.038	0.017	.029[b]
	STA	FUN	0.110	0.017	<.001[b]
	DYN	FUN	0.072	0.017	<.001[b]
RMS value	STA	DYN	0.017	0.011	.128
	STA	FUN	0.056	0.011	<.001[b]
	DYN	FUN	0.040	0.011	.001[b]

DYN, crown adjusted by virtual articulator with default parameters; FUN, crown adjusted by patient-specific motion; STA, crown adjusted by static occlusion. [a]Pairwise comparisons. [b]Mean difference significant ($P<.05$).

The digital workflow integrated the dynamic occlusion into the restoration design process. The occlusal surfaces were designed by using the static occlusion, the average-value virtual articulator, and the PSM, and the 3D deviation between the designed surfaces and the original wear facets was analyzed. The results indicated that the crowns designed by using the PSM had the lowest 3D deviation values. The STA crowns were designed by using only the static occlusion, and occlusal interferences may have been present during excursive movements. When the DYN crowns were designed, the positions of the maxillary casts were determined automatically by the algorithm and modified manually according to an average occlusal plane. The simulated movements with the average articulation and settings cannot represent the actual condition of the participants, resulting in undesirable results.

Negative errors happened in some crowns, with penetration of teeth during the static and dynamic occlusions. The TRIOS IOS operates on the principle of confocal microscopy and the projection of structured light (Ultrafast Optical Sectioning), capturing thousands of images to create a 3D digital cast.[38,39] The IOS can capture information at variable distances from the target at high speed, without powdering.[40] Generally, the number of images increases with an increased scan area. Cumulative errors in the stitching process with overlapping pictures result in decreased accuracy and a distorted dental arch. If arch distortions do occur, the software program must find a best fit from the 2 buccal occlusion data, where such a fit does not exist. Depending on the best fit algorithm, the deviations are averaged across the entire dental arch,[41] causing errors of the determined occlusion. Seo et al[42] scanned dental arches with the TRIOS 3 with color scanning capabilities after marking the occlusal contacts with articulating paper and reported that the virtual interocclusal record may demonstrate a mismatch against the actual occlusal contacts of the teeth, creating perforations and occlusal inaccuracy. The principle behind the PSM function has not been disclosed by the manufacturer. The maxillary and mandibular casts are aligned to a dynamic occlusal relationship by using the buccal surfaces of approximately 3 teeth or by using a few points during the PSM recording process, resulting in alignment errors. In addition, the digital casts were scanned without occlusal force, and the buccal occlusion data in maximum intercuspal position were scanned under occlusal force. In theory, tooth positions change under the 2 conditions because of bone distortion[43-45] and physiological tooth displacement[46-48] under occlusal loading. Occlusal contact is increased under occlusal force, leading to occlusal perforation by directly aligning the digital casts to the buccal occlusion data obtained under occlusal force. When recording PSM, tooth displacement under occlusal force can also occur, but physiological change cannot be simulated by the digital casts, and the occlusal contact of the dynamic occlusion simulated by the software program would also be greater than the actual condition. With the increased occlusal contact, there is a risk of designing restorations with few and even no occlusal contacts, leading to supraocclusion of the antagonist teeth. In future research, the virtual occlusion should be corrected according to the actual occlusal contacts, and the mandibular deformation and tooth displacement should be considered to produce an actual virtual patient module.

Limitations of the digital workflow to design restorations by using the PSM included that its limited application for the registration accuracy would be affected by increased horizontal and vertical overlap. In the present study, the maxillary and mandibular casts of individuals with increased horizontal and vertical overlap could not be automatically aligned to dynamic occlusal relationship, resulting in the failure of the PSM recording. Other limitations included that the PSM function could not detect all the interferences because no contact of the original posterior teeth of the participants with canine guidance occlusion was expected during protrusive and laterotrusive movements. Additional movement such as masticatory movement should be recorded, and the effect of these 3 design methods on the morphology of the wear facets of the participants with group function occlusion should be analyzed.

CONCLUSIONS

Based on the findings of this clinical study, the following conclusions were drawn:

1. The occlusal surface of crowns designed by using the patient-specific motion function had the best coincidence with the morphology of the wear facets on the original teeth compared with the crowns designed by using the static occlusion and the average-value virtual articulator.
2. The patient-specific motion function may be used to improve the occlusal relationship of mandibular first molar crowns.

REFERENCES

1. Lin PT, Jiao Y, Zhao SJ, Wang F, Li L, Yu F, et al. Occlusion and disocclusion time changes in single unit crowns designed by functional generated path technique: a randomised clinical trial. Sci Rep 2017;7:388.
2. Maruyama T, Nakamura Y, Hayashi T, Kato K. Computer-aided determination of occlusal contact points for dental 3-D CAD. Med Biol Eng Comput 2006;44:445-50.
3. Olthoff LW, van der Zel JM, de Ruiter WJ, Vlaar ST, Bosman F. Computer modeling of occlusal surfaces of posterior teeth with the CICERO CAD/CAM system. J Prosthet Dent 2000;84:154-62.
4. Berrendero S, Salido MP, Ferreiroa A, Valverde A, Pradies G. Comparative study of all-ceramic crowns obtained from conventional and digital impressions: clinical findings. Clin Oral Investig 2019;23:1745-51.
5. Christensen GJ. Will digital impressions eliminate the current problems with conventional impressions? J Am Dent Assoc 2008;139:761-3.
6. Nejatidanesh F, Amjadi M, Akouchekian M, Savabi O. Clinical performance of CEREC AC Bluecam conservative ceramic restorations after five years–a retrospective study. J Dent 2015;43:1076-82.
7. Koulivand S, Ghodsi S, Siadat H, Alikhasi M. A clinical comparison of digital and conventional impression techniques regarding finish line locations and impression time. J Esthet Restor Dent 2020;32:236-43.
8. Haddadi Y, Bahrami G, Isidor F. Evaluation of operating time and patient perception using conventional impression taking and intraoral scanning for crown manufacture: a split-mouth, randomized clinical study. Int J Prosthodont 2018;31:55-9.
9. Gjelvold B, Chrcanovic BR, Korduner E, Collin-Bagewitz I, Kisch J. Intraoral digital impression technique compared to conventional impression technique. A randomized clinical trial. J Prosthodont 2016;25:282-7.
10. Carrilho Baltazar Vaz IM, Pimentel Coelho Lino Carracho JF. Marginal fit of zirconia copings fabricated after conventional impression making and digital scanning: an in vitro study. J Prosthet Dent 2020;124:221-3.
11. Cheng CW, Ye SY, Chien CH, Chen CJ, Papaspyridakos P, Ko CC. Randomized clinical trial of a conventional and a digital workflow for the fabrication of interim crowns: an evaluation of treatment efficiency, fit, and the effect of clinician experience. J Prosthet Dent 2021;125:73-81.
12. Bandiaky ON, Le Bars P, Gaudin A, Hardouin JB, Cheraud-Carpentier M, Mbodj EB, et al. Comparative assessment of complete-coverage, fixed tooth-supported prostheses fabricated from digital scans or conventional impressions: a systematic review and meta-analysis. J Prosthet Dent 31 October 2020. doi: 10.1016/j.prosdent.2020.09.017. [Epub ahead of print].
13. Tabesh M, Nejatidanesh F, Savabi G, Davoudi A, Savabi O, Mirmohammadi H. Marginal adaptation of zirconia complete-coverage fixed dental restorations made from digital scans or conventional impressions: a systematic review and meta-analysis. J Prosthet Dent 2021;125:603-10.
14. Richter J, Mehl A. Evaluation for the fully automatic inlay reconstruction by means of the biogeneric tooth model. Int J Comput Dent 2006;9:101-11.
15. Kist S, Kollmuss M, Jung J, Schubert S, Hickel R, Huth KC. Comparison of ozone gas and sodium hypochlorite/chlorhexidine two-visit disinfection protocols in treating apical periodontitis: a randomized controlled clinical trial. Clin Oral Investig 2017;21:995-1005.
16. Duret F, Blouin JL, Duret B. CAD-CAM in dentistry. J Am Dent Assoc 1988;117:715-20.
17. Fasbinder DJ, Poticny DJ. Accuracy of occlusal contacts for crowns with chairside CAD/CAM techniques. Int J Comput Dent 2010;13:303-16.
18. Mehl A, Blanz V, Hickel R. Biogeneric tooth: a new mathematical representation for tooth morphology in lower first molars. Eur J Oral Sci 2005;113:333-40.
19. Mehl A, Blanz V, Hickel R. A new mathematical process for the calculation of average forms of teeth. J Prosthet Dent 2005;94:561-6.
20. Grant GT, Campbell SD, Masri RM, Andersen MR. Glossary of digital dental terms. J Prosthodont 2016;25:S2-9.
21. Cho S, Chang W. Mirror-image anterior crown fabrication with computer-aided design and rapid prototyping technology: a clinical report. J Prosthet Dent 2013;109:75-8.
22. Yoon TH, Chang WG. The fabrication of a CAD/CAM ceramic crown to fit an existing partial removable dental prosthesis: a clinical report. J Prosthet Dent 2012;108:143-6.
23. Kurbad A, Kurbad S. Cerec Smile Design–a software tool for the enhancement of restorations in the esthetic zone. Int J Comput Dent 2013;16:255-69.
24. Zandinejad A, Metz M, Stevens P, Lin W, Morton D. Virtually designed and CAD/CAM-fabricated lithium disilicate prostheses for an esthetic maxillary rehabilitation: a senior dental student clinical report. J Prosthet Dent 2015;113:282-8.
25. El KT, Nimmo A. Integrating conventional and CAD/CAM digital techniques for establishing canine protected articulation: a clinical report. J Prosthet Dent 2016;115:515-9.
26. Arslan Y, Karakoca NS, Bankoglu GM, Tamam E, Yilmaz H. Evaluation of biogeneric design techniques with CEREC CAD/CAM system. J Adv Prosthodont 2015;7:431-6.
27. Jedynakiewicz NM, Martin N. Functionally-generated pathway theory, application and development in Cerec restorations. Int J Comput Dent 2001;4:25-36.
28. Mehl A. A new concept for the integration of dynamic occlusion in the digital construction process. Int J Comput Dent 2012;15:109-23.
29. Kim J, Park J, Moon H. Complete assessment of occlusal dynamics and establishment of a digital workflow by using target tracking with a three-dimensional facial scanner. J Prosthodont Res 2019;1:120-4.
30. Shetty S. Virtual articulators and virtual facebow transfers: digital prosthodontics!!! J Indian Prosthodont Soc 2015;15:291.
31. Hsu MR, Driscoll CF, Romberg E, Masri R. Accuracy of dynamic virtual articulation: trueness and precision. J Prosthodont 2019;28:436-43.
32. Hugger A, Hugger S, Ruge S, John D, Kordass B. The rotation vs translation behavior during habitual opening and closing movements of the mandible and the relationship to movement paths of condylar points. Int J Comput Dent 2020;23:17-26.
33. Li L, Chen H, Li W, Wang Y, Sun Y. The effect of residual dentition on the dynamic adjustment of wear facet morphology on a mandibular first molar crown. J Prosthodont 2021;30:351-5.
34. Li L, Chen H, Zhao Y, Wang Y, Sun Y. Design of occlusal wear facets of fixed dental prostheses driven by personalized mandibular movement. J Prosthet Dent 03 February 2021. doi: 10.1016/j.prosdent.2020.09.055. [Epub ahead of print].
35. Lauren M, McIntyre F. 4D clinical imaging for dynamic CAD. Int J Dent 2013;2013:690265.
36. Valenti M, Schmitz JH. A reverse digital workflow by using an interim restoration scan and patient-specific motion with an intraoral scanner. J Prosthet Dent 2021;126:19-23.
37. Lee Y, Lee C, Shim J, Park J, Shin Y, Kim J, et al. Comparison between occlusal errors of single posterior crowns adjusted using patient specific motion or conventional methods. Appl Sci 2020;10:9140.
38. Seelbach P, Brueckel C, Wostmann B. Accuracy of digital and conventional impression techniques and workflow. Clin Oral Investig 2013;17:1759-64.
39. Logozzo S, Zanetti EM, Franceschini G, Kilpela A, Makynen A. Recent advances in dental optics - part I: 3D intraoral scanners for restorative dentistry. Opt Lasers Eng 2014;54:203-21.

40. Berrendero S, Salido MP, Valverde A, Ferreiroa A, Pradíes G. Influence of conventional and digital intraoral impressions on the fit of CAD/CAM-fabricated all-ceramic crowns. Clin Oral Investig 2016;20:2403-10.
41. Gintaute A, Keeling AJ, Osnes CA, Zitzmann NU, Ferrari M, Joda T. Precision of maxillo-mandibular registration with intraoral scanners in vitro. J Prosthodont Res 2020;64:114-9.
42. Seo JM, Oh WS, Lee JJ. A technique for verifying the accuracy of the virtual mounting of digital scans against the actual occlusal contacts. J Prosthet Dent 2019;121:729-32.
43. Korioth TW, Hannam AG. Deformation of the human mandible during simulated tooth clenching. J Dent Res 1994;73:56-66.
44. Choi AH, Conway RC, Taraschi V, Ben-Nissan B. Biomechanics and functional distortion of the human mandible. J Investig Clin Dent 2015;6:241-51.
45. Wolf L, Bergauer B, Adler W, Wichmann M, Matta RE. Three-dimensional evaluation of mandibular deformation during mouth opening. Int J Comput Dent 2019;22:21-7.
46. Hidaka O, Iwasaki M, Saito M, Morimoto T. Influence of clenching intensity on bite force balance, occlusal contact area, and average bite pressure. J Dent Res 1999;78:1336-44.
47. De Oliveira BF, Seraidarian PI, de Oliveira SG, Landre J, Pithon MM, Oliveira DD. Tooth displacement in shortened dental arches: a three-dimensional finite element study. J Prosthet Dent 2014;111:460-5.
48. Gomes DOS, Seraidarian PI, Landre JJ, Oliveira DD, Cavalcanti BN. Tooth displacement due to occlusal contacts: a three-dimensional finite element study. J Oral Rehabil 2006;33:874-80.

Corresponding author:
Dr Yuchun Sun
Center of Digital Dentistry
Peking University School and Hospital of Stomatology
22 Zhongguancun Ave South
Haidian District
Beijing 100081
PR CHINA
Email: kqsyc@bjmu.edu.cn

https://doi.org/10.1016/j.prosdent.2021.06.048