# Occlusal Assessment of Zirconia Crowns Designed with the Digital Articulator and Traditional Methods

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*Purpose:* To evaluate and compare the occlusal fit of zirconia crowns designed using a digital articulator method and the traditional method in a self-controlled clinical trial. *Materials and Methods:* Two zirconia crowns each were prepared for 12 patients with a single posterior tooth defect using two different methods: a digital articulator method and the traditional method. In the traditional method, casts were scanned using a model scanner, and the relative positions of the maxillary and mandibular arches were determined by the intercuspal occlusion of the casts. In the digital articulator method, casts were mounted on a mechanical articulator and scanned, and the relative positions were determined by their respective positions in the articulator. Additional dynamic occlusal adjustments of the digital articulator crowns were performed. Both groups of zirconia crowns were milled in a five-axis milling machine. The time required for occlusal adjustments, the occlusal contacts, the occlusal contact distributions, the number of occlusal contacts, the relative occlusal forces, and patient satisfaction (visual analog scale score) were evaluated. Wilcoxon test, McNemar test, and paired *t* test were used to compare the parameters between the two methods. *Results:* The occlusal adjustment times for the digital articulator and traditional method crowns were 327 ± 226 seconds and 395 ± 338 seconds, respectively (*P* > .05). There were no significant differences in occlusal contacts, occlusal contact distributions, number of occlusal contacts, relative occlusal forces, or VAS scores between the two methods (*P* > .05). *Conclusion:* A digital articulator method for single-crown restoration was applied successfully. Crowns fabricated using a digital articulator or the traditional method can achieve acceptable occlusal fit for single-crown restorations. *Int J Prosthodont 2021;34:13–20. doi: 10.11607/ijp.6570*

Restoration of an occlusion is an important issue in restorative dentistry.[1,2] Improper occlusal treatment may lead to occlusal trauma, interferences, and various other problems. Occlusion has a close relationship with the dental tissues, the temporomandibular joints, and the masticatory muscles.[3,4] Nowadays, through intraoral or model scanning and digital designing and manufacturing, different types of precise restorations can be fabricated.[5] However, during the process of digital designing, the software traditionally removes only the occlusal parts that produce static interferences with antagonist teeth and do not analyze dynamic occlusion.[6] Additionally, only a customized occlusal plane and mean-value articulator can be used to identify and adjust lateral interferences.[7,8] These limitations lead to requirements of more time and effort during clinical adjustments of the restorations.[9]

The mechanical articulator is a commonly used auxiliary device in prosthesis design and fabrication.[10] With the application of CAD/CAM technology in dentistry,

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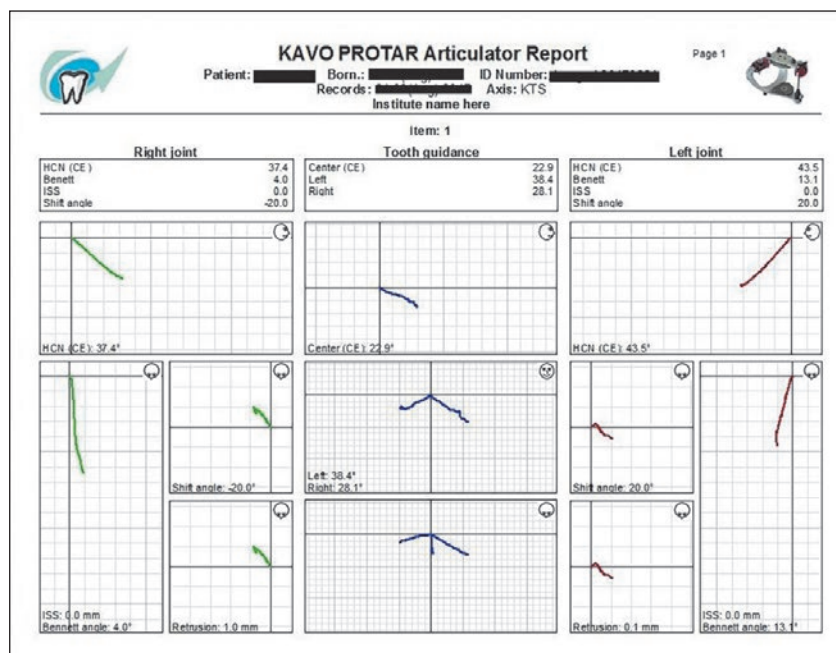*Email: drzhanglei@yeah.net*

**Fig 1** Condylar parameters of mandibular movements measured by the ARCUSdigma system. The bite fork used is also used for mounting casts, and the value of the horizontal condylar slope and the Bennett angle are set for the digital articulator in the CAD software.
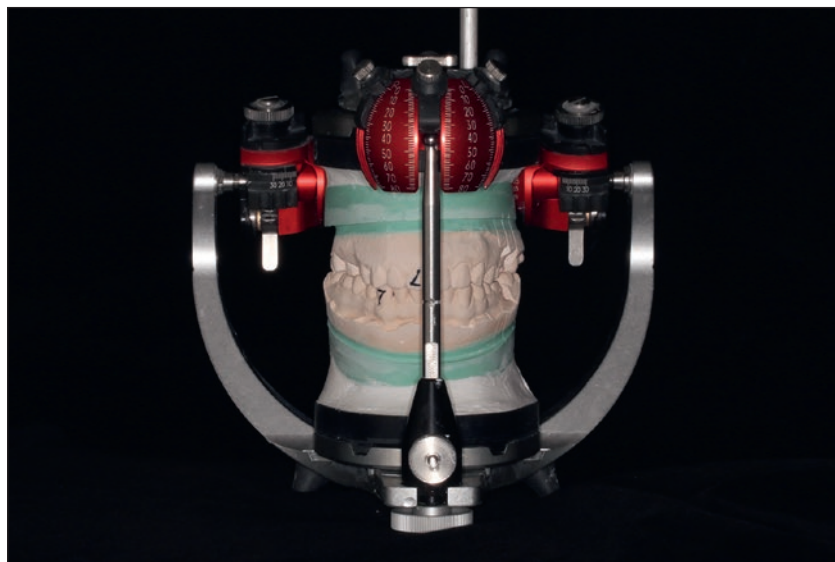


**Fig 2** Mounting of the maxillary and mandibular casts using the recorded values on the articulator (PROTARevo 7).

researchers began to explore methods for updating mechanical articulators with computer software and established various initial virtual articulator systems.[11–13] The digitalized mechanical articulator was called the "digital articulator" or the "mathematically simulated articulator."[13] The digital articulator is a direct tool that guides occlusal adjustment and has multiple advantages over the mechanical articulator.[14] When the digital articulator is combined with dental computer-aided design (CAD) software, both static and dynamic occlusion can be taken into consideration, which can significantly improve the quality of the clinical prosthesis and address the difficulties associated

with occlusal adjustments in complicated cases.[15,16]

Considerable research has been performed to find better ways of using a virtual articulator and enhancing its accuracy.[17–22] The mechanism of operation of the digital articulator is relatively complex and highly dependent on software and hardware; therefore, few studies have evaluated the accuracy of digital articulators, especially those with fully adjustable parameters, in clinical restorations. The objective of this study was to assess the occlusal accuracy of crowns designed using a digital articulator and to compare it to crowns fabricated using the traditional method. The null hypothesis was that the occlusion of complete crowns fabricated with the digital articulator method compared to the traditional method would have no differences in occlusal fit, manifesting as no differences in occlusal adjustment time, occlusal contacts, relative occlusal force (ROF), or patients' subjective evaluations.

## MATERIALS AND METHODS

### Study Participants
This study was registered with the Chinese Clinical Trial Registry and the World Health Organization (ChiCTR-INR-16008559). Ethics committee approval was obtained from the Peking University School of Stomatology Biomedical Institutional Review Board PKUSSIRB-201523086). This study was conducted in accordance with the tenets of the Declaration of Helsinki and the Good Clinical Practice guidelines. Informed consent was provided by each participant.

The sample size calculation was based on the number of patients required to demonstrate a 120-second difference in mean occlusal adjustment time between the two methods using paired-sample t test. Based on a significance level of .05, a power of 80%, and an SD of 132 seconds for occlusal adjustment

time,[23] the sample size was calculated to be a total of 12 for both methods.

The inclusion criteria were as follows: patients *(1)* aged between 18 and 60 years of age; *(2)* requiring a complete crown restoration on a single tooth; *(3)* with no clinical symptoms (eg, sensitive percussion, peripyema, pain, etc); *(4)* with adequate root canal treatment; and *(5)* with good oral hygiene.

The exclusion criteria were as follows: patients *(1)* exhibiting bruxism, clenching, or grinding; *(2)* with acute or chronic temporomandibular joint disorders; *(3)* with sensory and/or mental abnormalities; *(4)* who were pregnant or lactating; *(5)* with other factors that could potentially affect the restorations (such as severe cardiocerebral vascular diseases, coagulation abnormalities, etc); and *(6)* in whom the opposite tooth had been restored with an implant-supported crown or partial denture.

## Tooth Preparation

For each patient, the selected tooth was prepared for a monolithic zirconia crown by preparing a 1.0-mm perpendicular chamfer with a rounded interior line angle, an occlusal reduction of 1.0 to 1.5 mm, and a 6- to 10-degree convergence angle. The height of the prepared tooth was verified to be no less than 2 mm, and the preparation finish line was placed above the gingival level.[24] Impressions of the maxillary and mandibular arches were made with silicon impression material (Variotime Monophase/Light Flow, Heraeus Kulzer) and were poured in type 4 dental stone (Pemaco). All clinical procedures were performed by the same dentist specialized in prosthodontics (R.Z.).

## Model Scanning and CAD

For each patient, the maxillary and mandibular casts were scanned with a model scanner (D2000, 3Shape), and the crowns were designed using two different methods: a digital articulator and the traditional method.

While using a digital articulator, the ARCUSdigma system (KaVo) was used to measure and reproduce jaw movements (Fig 1). Condylar parameters, including the right and left horizontal condylar guidance, curved Bennett angles, and Bennett shift angles, were measured. The maxillary and mandibular casts were mounted using the recorded parameters on a mechanical articulator (PROTARevo 7, KaVo; Fig 2).

In order to calibrate the digital articulator with the mechanical articulator, a calibration process was performed according to the manufacturer's instructions. Occlusal transfer calibration objects (3Shape) were attached with type 2 low-expansion stone (ZERO arti, Dentona) to the mounting plates of the mechanical articulator (Fig 3), and the mountings were transferred to the model scanner (D2000) using the transfer plates for PROTARevo. The calibration process was automatically completed by the



**Fig 3** Mounting of the 3Shape occlusal transfer calibration object on the articulator.
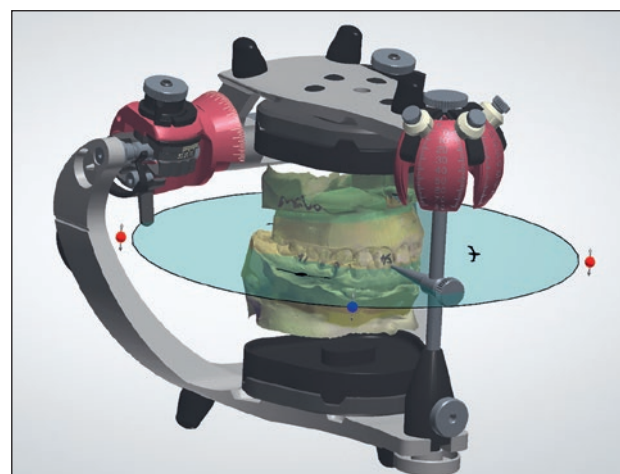


**Fig 4** Digital casts mounted on the digital articulator in the corresponding positions calibrated from the mechanical articulator.

software. Following the manufacturer's suggestions, the scanning of the maxillary and mandibular casts fixed on the transfer plates was completed with a specialized scanning process for the digital articulator. The relative positions of the digital casts in the digital articulator were determined by automatic calculation (Fig 4). An appropriate tooth element was selected from the library and was shaped to be in harmony with the remaining dentition. The cement space was set to 60 μm at the axial and occlusal surfaces and 20 μm at the margins.[25] Proximal contacts were adjusted to adjacent teeth, and the intercuspal occlusion (ICO) was adjusted to fit with the antagonist teeth to 0 μm. After a preliminary design was obtained, the digital articulator was used. The values
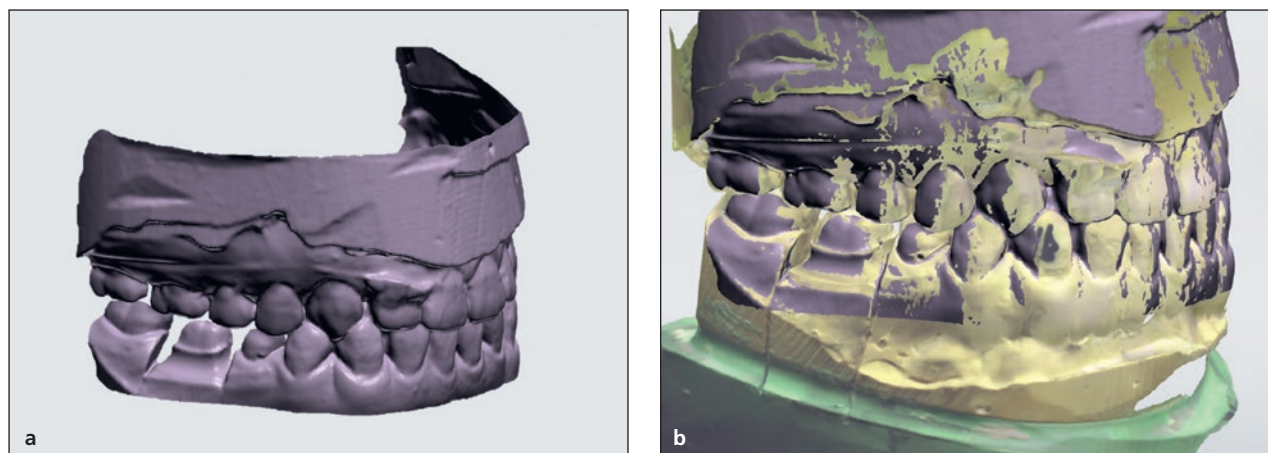
**Fig 5** The traditional method achieved occlusion by scanning the buccal side of the maxillary and mandibular casts. *(a)* Digital scanning of the buccal side. *(b)* The occlusal relation of the maxillary and mandibular arches after superimposition.

of condylar guidance from the mechanical articulator were entered into the software, and mandibular movements, including protrusive and lateral movements, were simulated for dynamic occlusal adjustments. Any interference on the crown was adjusted, and the surface of the crown was finished and smoothed.

In the traditional method, the maxillary and mandibular casts were transferred to the model scanner with simple fixation on the platform. The casts were scanned separately according to the manufacturer's suggestions. Next, the maxillary and mandibular casts were placed in maximum intercuspation (ICP) and were affixed with wax from the lingual side. The relative occlusal positions were obtained by scanning the buccal sides of the positioned casts (Fig 5). An appropriate tooth element was selected from the library and was shaped to be in harmony with the remaining dentition. Proximal contacts were adjusted to adjacent teeth, the ICO was adjusted automatically to fit with the antagonist teeth to 0 µm, and the surface of the crown was finished and smoothed.

The data of the two crowns were exported into standard tessellation language (STL) format and were sent to a five-axis milling machine (Zenotec select hybrid, Wieland Dental). Intrinsically colored monolithic zirconia blocks (Zenostar, Wieland Dental) were milled and sintered according to the manufacturer's recommendations.

### Crown Evaluations

During the clinical try-in, the patients and the dentist were blinded to the design methods used to fabricate the two crowns. The two crowns for each patient were randomly labeled by a third person (Y.S.) in advance. After proximal and internal fitting, the occlusal fit of each zirconia crown was evaluated using articulating paper, and patient feedback was obtained. Occlusal adjustment

was completed with a diamond bur, and the adjustment time was recorded.

*Articulating paper examination*
The ICO and lateral interferences in functional movements were checked and recorded to guide occlusal adjustments. Identification of occlusal contacts in the maximum ICP was performed via a two-phase method using both 100-µm and 12-µm articulating papers (BK-51 Blue and Arti-Fol BK-25 Red, Bausch). Clinical photographs were taken immediately, and lateral interferences were identified during functional movements using two colors of the 100-µm articulating paper (BK-51 Blue and BK-52 Red, Bausch). After randomization and numbering of the clinical photographs of all patients, two senior professional prosthodontists who were blinded to the grouping and processes of the study made separate evaluations. The occlusal contacts (OC), occlusal contact distributions (OD) (Table 1), and number of occlusal contacts (NC) were determined based on the modified criteria of the FDI World Dental Federation,[26] and inter-rater agreement was assessed using weighted $\alpha$ statistics (linear weights). If there was a high degree of consistency among the evaluators, the evaluation results of either rater were selected for analysis; otherwise, the evaluation results of both evaluators were analyzed separately. The OC and OD scores of the digital articulator crowns before occlusal adjustment (VA[B]), the traditional method crowns before occlusal adjustment (LB[B]), the digital articulator crowns after occlusal adjustment (VA[A]), and the traditional method crowns after occlusal adjustment (LB[A]) were recorded.

### T-Scan and Electromyography Examinations

After occlusal adjustments of the two groups of crowns, T-Scan (T-Scan III, Tekscan) and electromyography (EMG)

**Table 1** Evaluation Criteria for Occlusal Contacts and Occlusal Contact Distribution in Intercuspal Occlusion

| Score | Occlusal contacts | Occlusal contact distribution |
|---|---|---|
| 4 (excellent) | Occlusal contact points on the crown and adjacent teeth; equally strong contacts (both 100-μm and 12-μm articulating paper imprints exist on the crown and adjacent teeth); no supra- or infraocclusion. | Good occlusal contact distribution. Occlusal contacts between supporting cusps and opposing fossa or ridge. |
| 3 (good) | Occlusal contact points on the crown and adjacent teeth; unequal strong contacts (only 100-μm articulating paper imprints exist on the adjacent teeth). | Individual occlusal contact points missing or deviated; occlusal contacts on the principal supporting cusp; crown is functional. |
| 2 (satisfactory) | Contact points only on the crown (crown too high = supraocclusion). | No occlusal contacts on supporting cusps; contacts present on other parts of the occlusal surface. |
| 1 (unsatisfactory) | No occlusal contact points on the crown (infraocclusion). | No occlusal contacts or the distribution is detrimental to the stability of the crown. |

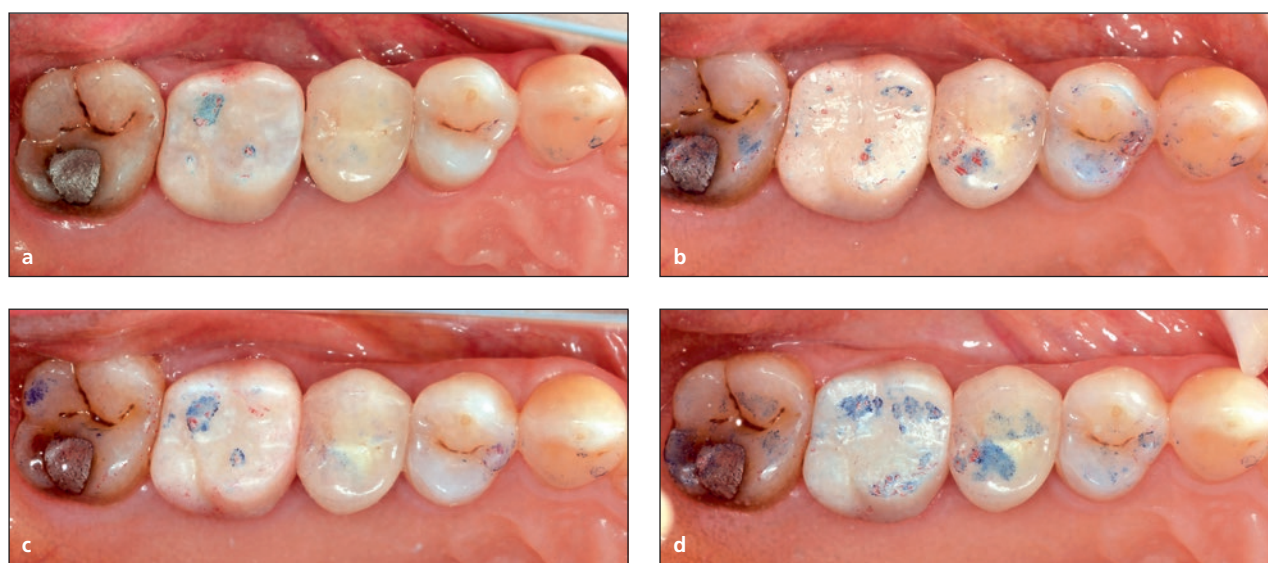These criteria were modified based on the criteria of the FDI World Dental Federation.[26]



**Fig 6** Occlusion of the mandibular right first molar after complete crown restoration (100-μm blue and 12-μm red articulating paper). *(a)* Occlusal contact of the complete crown designed using a digital articulator method in the intercuspal position after restoration and *(b)* after occlusal adjustment. *(c)* Occlusal contact of the complete crown designed using the traditional method in the intercuspal position after restoration and *(d)* after occlusal adjustment.

(BioEMG III, BioRESEARCH) examinations were performed. The T-Scan III is an efficient tool for determining OC locations and for measuring relative force intensities over time.[27] The subjects were seated in a relaxed upright position with the Frankfurt plane oriented horizontally.[28] The appropriate sensors for the T-Scan (100 μm) were positioned close to the maxillary occlusal plane,[29] and the proper sensitivity range for acquisition of occlusal data was established. Subjects were instructed to close in the ICP, while the ROF and jaw muscle EMG in the maximum occlusal contact frame were recorded (in μV) three times. To ensure data consistency, the detection range was maintained in the same location with respect to the patient's dentition.

*Patients' subjective evaluations*

During the clinical try-in, patients were instructed to evaluate the occlusal comfort of the crowns on a 100-mm visual analog scale (VAS) before and after occlusal adjustment. A distance of 100 mm was considered "perfect," and 0 was considered "intolerable." The distance in millimeters between the 0 point and the patient's mark on the line was measured and then converted to VAS score (0 to 100).

After evaluation, both groups of crowns were transferred to the laboratory and were polished, and the patient was asked to choose between the zirconia crown designed using the digital articulator and the crown

**Table 2** Number of Crowns With and Without Lateral Interferences in the Two Groups

| Traditional method | Digital articulator | | P |
| --- | --- | --- | --- |
| | Lateral interference | No lateral interference | |
| Lateral interference | 6 | 2 | > .05 |
| No lateral interference | 3 | 1 | |

designed using the traditional method for cementation (RelyX U200, 3M ESPE).

## Statistical Analysis

Data were collected and analyzed using SPSS 20.0 (IBM). Wilcoxon test was used to compare the OC, OD, and NC between the digital articulator and traditional method crowns, represented as median ($Q_{25}$, $Q_{75}$). McNemar test was used to compare the functional interferences between the two groups of crowns. Paired $t$ tests were used to compare the ROF and EMG values, represented in mean ± SD. For all analyses, $P < .05$ was considered to be statistically significant.

## RESULTS

Twelve patients (5 women, 7 men; mean age 32.25 years) and 12 teeth were included (8 molars and 4 premolars). A typical case is shown in Fig 6. For final cementations, 7 crowns made with the digital articulator method and 5 made with the traditional method were chosen by the patients.

## Interferences and Occlusal Adjustment Time

Table 2 shows the number of crowns with and without lateral interferences in the two groups. There were no significant differences in functional interferences between the two groups of crowns ($P > .05$). Occlusal adjustment times for the digital articulator and traditional method crowns were 327 ± 226 seconds and 395 ± 338 seconds, respectively; however, these times were not significantly different ($P > .05$).

## Articulating Paper Evaluation

The weighted κ (linear weight) values for OC, OD, and NC, as rated by two dentists, were 0.858, 0.721, and 0.746, respectively, which indicated high agreement between the two raters. Scores before and after occlusal adjustment of the two groups of crowns are shown in Table 3. The results indicated that there were no significant differences in the OC and OD scores between the two groups of crowns before and after occlusal adjustments (both $P > .05$). The median ($Q_{25}$, $Q_{75}$) NC data for

VA(B), LB(B), VA(A), and LB(A) were 3 (3, 4), 4.5 (3.25, 5), 3 (3, 4), and 4 (3, 4.75), respectively. There were no statistically significant differences between the NC of VA(B) and LB(B) or the NC of VA(A) and LB(A) ($P > .05$).

## T-Scan and EMG Evaluation

After occlusal adjustment, the ROFs of the digital articulator crowns (11.08% ± 6.59%) and the traditional method crowns (10.38% ± 6.26%) were not significantly different ($P > .05$).

The raw mean and SD EMG values of all tested muscles are shown in Table 4. The EMG values on both sides of the masseter and anterior temporalis muscles were not significantly different between the digital articulator and traditional method crowns ($P > .05$).

## Patients' Subjective Evaluations

The VAS scores for the digital articulator and traditional method crowns were not significantly different ($P > .05$) before (digital articulator crown: 64.6 ± 26.4; traditional method crown: 71.2 ± 25.3) or after (digital articulator crown: 86.4 ± 13.1; traditional method crown: 90.9 ± 9.6) occlusal adjustment.

## DISCUSSION

The purpose of this study was to perform a clinical occlusal assessment of crowns fabricated using a digital articulator and the traditional method. During the clinical occlusal evaluation, no significant differences were observed between the two groups of crowns regarding occlusal adjustment time, articulating paper examination, T-Scan and EMG examinations, and patients' subjective evaluations. The results indicate that single complete crowns fabricated using a digital articulator meet clinical standards but show no advantages over crowns fabricated using the traditional method. The hypothesis that the occlusion of complete crowns fabricated using a digital articulator and that of crowns fabricated using the traditional method would have no differences in occlusal fit was accepted.

It was speculated that the digital articulator would show some advantages over the traditional method in occlusion of the crowns in dynamic functional movements because it is able to transfer the individual hinge axis and to simulate mandibular movements via jaw trackers. However, in the present study, no significant differences in the number of crowns with and without lateral interferences or in occlusal adjustment time were observed. First, this could be due to errors in mechanical occlusion (which exist in both methods), which could cause inaccuracies at all stages of crown fabrication, including impression-making, impression-pouring, mounting on the articulator, designing, and milling. Interferences could still occur due to supraocclusion

**Table 3** Occlusal Contacts (OC) and Occlusal Contact Distribution (OD) Scores for Intercuspal Occlusion Before and After Restoration of Intercuspal Occlusion According to One Rater

| | OC | | | | OD | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Score | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | Sum |
| VA(B)[a] | 0 | 3 | 6 | 3 | 0 | 2 | 1 | 9 | 12 |
| LB(B)[a] | 0 | 4 | 4 | 4 | 0 | 1 | 4 | 7 | 12 |
| VA(A)[b] | 0 | 0 | 0 | 12 | 0 | 1 | 1 | 10 | 12 |
| LB(A)[b] | 0 | 0 | 0 | 12 | 0 | 0 | 1 | 11 | 12 |

Data are reported as number of crowns. VA(B) = digital articulator crown before occlusal adjustment; LB(B) = traditional method crown before occlusal adjustment; VA(A) = digital articulator crown after occlusal adjustment; LB(A) = traditional-method crown after occlusal adjustment.
The same superscript letter denotes no significant differences in OC or OD scores between the two groups of crowns according to Wilcoxon test.

**Table 4** Mean ± SD Electromyography Values (µV) for the Digital Articulator and Traditional Method Crowns in the T-Scan Maximum Occlusal Area Frame

| | MA | | TA | |
|---|---|---|---|---|
| | Left | Right | Left | Right |
| VA | 69.39 ± 40.8 | 65.04 ± 26.3 | 151.25 ± 68.2 | 144.24 ± 79.3 |
| LB | 73.20 ± 45.7 | 73.58 ± 26.7 | 165.18 ± 67.6 | 151.71 ± 78.0 |
| t | −0.63 | −1.89 | −1.57 | −0.92 |
| P | .54 | .09 | .15 | .38 |

MA = masseter muscles; TA = anterior temporalis muscles; VA = digital articulator; LB = traditional method.

of the crowns, although the inclinations of cusps were designed to avoid lateral interferences. Further, errors could occur during recording of functional movements. Lei et al[30] evaluated the accuracy of the PROTARevo 7 articulator, adjusted using parameters acquired from the ARCUSdigma system, and found that during mandibular laterotrusions, horizontal occlusal errors reached a maximum of 14.80 ± 1.24 degrees and that vertical occlusal errors reached a maximum of 191 ± 10 µm at the mandibular second molar of the working side. Additionally, for a single-crown restoration on a posterior tooth, jaw movement is mainly guided both by the patient's remaining teeth and the condyle. The advantage of recording accurate condylar movements in a digital articulator method becomes less prominent when natural tooth guidance is present. Accordingly, it is assumed that for patients with loss of natural tooth guidance and of morphologic reference of adjacent teeth (such as more severe dentition defects, especially multiple anterior teeth defects) and for full-mouth rehabilitation cases, the digital articulator method may be more advantageous than the traditional method.[21]

When the digital articulator is used for designing complete crowns, the relative occlusal positions of the maxillary and mandibular casts can be automatically determined by the software. However, this automatic process may cause more inaccuracies compared to the traditional buccal bite-scanning registration, which obtains the occlusion by superimposing casts and scanning buccal sides of bites. In a study conducted by Solaberrieta et al,[19] the mean occlusal error in transferring the maxillary cast to the digital articulator was 0.752 mm. The authors recognized that this precision was sufficient for orthodontic treatment, but that more precision is required for prosthetic treatment. However, the computer study by Stavness et al[31] suggested that mathematic simulation utilizing interocclusal "bite" registrations can closely replicate the primary movements of casts. In the present study, even if the fully adjustable articulator was used and values of condylar parameters were obtained by the mandible movement tracker, the transfer process from the mechanical to the digital articulator could still lead to errors and variations, which could be due to the material limitations of the impression and gypsum casts and the simplification of complicated mandibular movements.[6] From the results of the present study, no differences in OC, OD, NC, or ROF before adjustment between the two groups of crowns were observed,

indicating that the error and inaccuracy of the digital articulator method is relatively acceptable for clinical use.

To the best of the authors' knowledge, this study for the first time explored the accuracy of single crown design and fabrication using a digital articulator method. However, the accuracy of this process should be further improved to reduce errors and meet clinical needs that require higher precision. Further exploration should focus on the application of digital articulators in cases that require multiple restorations or prostheses that change anterior guidance.

## CONCLUSIONS

Overall, these results demonstrate that both the digital articulator and traditional methods can achieve acceptable occlusal fit for single-crown restorations. No significant difference in any occlusal parameter was found in this study. Further research is needed for verification, especially for multiple-tooth restorations.

## ACKNOWLEDGMENTS

## REFERENCES

1. Gray HS. Occlusion and restorative dentistry: Part II. N Z Dent J 1993;89:87–91.
2. Gray HS. Occlusion and restorative dentistry: Part 1. N Z Dent J 1993;89:61–65.
3. Grinin VM. The concept of the pathogenesis of occlusive disorders in diseases of the temporomandibular joint [in Russian]. Stomatologiia (Mosk) 1995;74:29–32.
4. Kvinnsland I, Heyeraas KJ. Effect of traumatic occlusion on CGRP and SP immunoreactive nerve fibre morphology in rat molar pulp and periodontium. Histochemistry 1992;97:111–120.
5. Ramiro GP, Coronel CA, Navarro AF, Hassan B, Tamimi F. Computer-aided design in restorative dentistry. In: Tamimi F, Hirayama H (eds). Digital Restorative Dentistry. Cham: Springer, 2019:41–54.
6. Brawek PK, Wolfart S, Endres L, Kirsten A, Reich S. The clinical accuracy of single crowns exclusively fabricated by digital workflow—the comparison of two systems. Clin Oral Investig 2013;17:2119–2125.
7. Jedynakiewicz NM, Martin N. Functionally-generated pathway theory, application and development in Cerec restorations. Int J Comput Dent 2001;4:25–36.
8. Tamim H, Skjerven H, Ekfeldt A, Rønold HJ. Clinical evaluation of CAD/CAM metal-ceramic posterior crowns fabricated from intraoral digital impressions. Int J Prosthodont 2014;27:331–337.
9. Krahenbuhl JT, Cho SH, Irelan J, Bansal NK. Accuracy and precision of occlusal contacts of stereolithographic casts mounted by digital interocclusal registrations. J Prosthet Dent 2016;116:231–236.
10. Millstein PL. The articulator: A diagnostic instrument. J Mass Dent Soc 2002;50:24–25.
11. Solaberrieta E, Etxaniz O, Minguez R, Muniozguren J, Arias A. Design of a Virtual Articulator for the Simulation and Analysis of Mandibular Movements in Dental CAD/CAM [Proceedings of the 19th CIRP Design Conference—Competitive Design, 30–31 Mar, Cranfield University]. Cranfield, UK: Cranfield University, 2009.
12. Solaberrieta E, Arias A, Barrenetxea L, Etxaniz O, Minguez R, Muniozguren J. A Virtual Dental Prostheses Design Method Using a Virtual Articulator [Proceedings of the DESIGN 2010, the 11th International Design Conference, 17–20 May 2010, Dubrovnik, Croatia]. Glasgow: The Design Society: 2010:443–452.
13. Gugwad RS, Basavakumar M, Abhijeet K, Arvind M, Sudhindra M, Ramesh C. Virtual articulators in prosthodontics. Int J Dental Clinics 2011;3:39–41.
14. Kwon TG, Choi JW, Kyung HM, Park HS. Accuracy of maxillary repositioning in two-jaw surgery with conventional articulator model surgery versus virtual model surgery. Int J Oral Maxillofac Surg 2014;43:732–738.
15. Koralakunte PR, Aljanakh M. The role of virtual articulator in prosthetic and restorative dentistry. J Clin Diagn Res 2014;8:ZE25–EZ28.
16. Solaberrieta E, Otegi JR, Goicoechea N, Brizuela A, Pradies G. Comparison of a conventional and virtual occlusal record. J Prosthet Dent 2015;114:92–97.
17. Solaberrieta E, Garmendia A, Minguez R, Brizuela A, Pradies G. Virtual facebow technique. J Prosthet Dent 2015;114:751–755.
18. Solaberrieta E, Mínguez R, Barrenetxea L, Etxaniz O. Direct transfer of the position of digitized casts to a virtual articulator. J Prosthet Dent 2013;109:411–414.
19. Solaberrieta E, Mínguez R, Barrenetxea L, Otegi JR, Szentpétery A. Comparison of the accuracy of a 3-dimensional virtual method and the conventional method for transferring the maxillary cast to a virtual articulator. J Prosthet Dent 2015;113:191–197.
20. Solaberrieta E, Minguez R, Barrenetxea L, Sierra E, Etxaniz O. Computer-aided dental prostheses construction using reverse engineering. Comput Methods Biomech Biomed Engin 2014;17:1335–1346.
21. Solaberrieta E, Minguez R, Etxaniz O, Barrenetxea L. Improving the digital workflow: Direct transfer from patient to virtual articulator. Int J Comput Dent 2013;16:285–292.
22. Solaberrieta E, Otegi JR, Mínguez R, Etxaniz O. Improved digital transfer of the maxillary cast to a virtual articulator. J Prosthet Dent 2014;112:921–924.
23. Ender A, Mörmann WH, Mehl A. Efficiency of a mathematical model in generating CAD/CAM-partial crowns with natural tooth morphology. Clin Oral Investig 2011;15:283–289.
24. Perakis N, Belser UC, Magne P. Final impressions: A review of material properties and description of a current technique. Int J Periodontics Restorative Dent 2004;24:109–117.
25. Ahrberg D, Lauer HC, Ahrberg M, Weigl P. Evaluation of fit and efficiency of CAD/CAM fabricated all-ceramic restorations based on direct and indirect digitalization: A double-blinded, randomized clinical trial. Clin Oral Investig 2016;20:291–300.
26. Hickel R, Peschke A, Tyas M, et al. FDI World Dental Federation—Clinical criteria for the evaluation of direct and indirect restorations. Update and clinical examples. J Adhes Dent 2010;12:259–272.
27. Setz J, Geis-Gerstorfer J. Properties of a measuring system for digital occlusion diagnosis [in German]. Dtsch Zahnarztl Z 1990;45(7 spec no):s65–s66.
28. Christensen LV, Kundinger KK. Activity index and isometric contraction velocity of human jaw muscles. J Oral Rehabil 1991;18:555–561.
29. Kerstein RB, Radke J. The effect of disclusion time reduction on maximal clench muscle activity levels. Cranio 2006;24:156–165.
30. Lei C, Lan G, Pu W, Haili H, Lian Y. Accuracy of PROTARevo 7 articulator adjusted by using parameters from ArcusDigma system. J Hebei Medical University 2013;34:538–541.
31. Stavness IK, Hannam AG, Tobias DL, Zhang X. Simulation of dental collisions and occlusal dynamics in the virtual environment. J Oral Rehabil 2016;43:269–278.