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CLINICAL RESEARCH

Design of occlusal wear facets of fixed dental prostheses driven by personalized mandibular movement

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ABSTRACT

Statement of problem. Existing virtual articulators simulate mandibular movement by using various parameters and are used to design restorations. However, they are not able to reproduce actual patient movements, and the designs of occlusal wear facets by them and by personalized mandibular movement have not been compared.

Purpose. The purpose of this clinical study was to establish a clinical application protocol for a virtual articulator based on previous research and to evaluate the accuracy of the occlusal wear facets designed by it.

Material and methods. The gypsum casts of 12 participants were scanned with a cast scanner as the original data. A single crown, 3-unit splinted crowns, a 5-unit fixed partial denture, and a fixed complete denture were virtually prepared on the digital mandibular casts by using the Geomagic Studio 2013 software program. High points were created at the wear facets, and corresponding digital wax patterns with occlusal interferences were generated. The exocad software program was used to design corresponding restorations with the copy method. Static (STA restoration) and dynamic (DYN restoration) occlusal adjustments were carried out with the built-in virtual articulator. The mandibular movements of participants were recorded by the novel virtual articulator system, and the occlusal surfaces of the digital wax patterns were adjusted (FUN restoration). The restorations adjusted with the 3 methods were compared with the original data. The mean value and root mean square (RMS) of 3D deviation and positive volumes (V+) in the occlusal direction were measured. Depending on the normality, 1-way ANOVA and the Kruskal-Wallis test were used to analyze the influence of occlusal surface design methods on the morphology of occlusal wear facets (α=.05).

Results. The mean deviation of the 4 kinds of STA restorations ranged from 0.19 mm to 0.22 mm, the DYN restorations from 0.13 mm to 0.17 mm, and the FUN restorations from 0.03 mm to 0.09 mm. A significant difference was found between the STA and FUN restorations of the 3-unit splinted crowns and 5-unit fixed partial dentures (*P*=.013, *P*=.021). The mean values of 3D deviation and V+ decreased from the STA group to the DYN group and then to the FUN group. The RMS and V+ were statistically similar (*P*>.05).

Conclusions. The preliminary results of the study indicate that the FUN 3-unit splinted crowns and 5-unit fixed partial dentures designed with the self-developed virtual articulator were better than the STA restorations. The FUN restorations were more coincident with the morphology of the wear facets on the original teeth. (J Prosthet Dent 2022;128:33-41)

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Clinical Implications

The virtual articulator developed had an advantage over a mathematically simulated virtual articulator. A facebow was not necessary to mount casts. In addition, it reproduced actual mandibular movements of the participants instead of approximate simulations based on articulator parameters. The novel virtual articulator, with further development, may improve clinical treatment with fixed restorations.

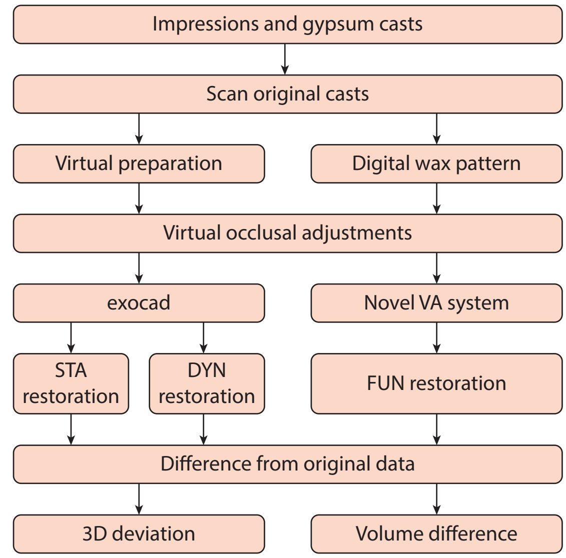

Figure 1. Experimental design. DYN, restoration adjusted by virtual articulator with default parameters; FUN, restoration adjusted by individual mandibular movement; STA, restoration adjusted by static occlusion; VA, virtual articulator.

The design of a functional occlusal surface is an essential part of prosthetic dentistry. The occlusal design of restorations should be in harmony with the remaining dentition, establish interference-free function of all parts of the stomatognathic system, and provide natural-looking morphology.[1-3] It should restore functional grooves and cusps to reconstruct masticatory function, wear facets adapted to mandibular movement, and marginal ridges coordinated with adjacent teeth to avoid food impaction.[4-6] Wear facets are caused by tooth-to-tooth friction or friction between teeth and exogenous agents.[7,8] Wear facets result from actual jaw movement and the resistance of antagonists and are functional surfaces that guide jaw movement from occlusal contacts.[9,10] Information about food ingestion and mastication behavior during the lifespan of an individual is encoded in the dental occlusal wear pattern.[11] It is important to restore the wear facets of damaged teeth.[12]

The design of ideal occlusal wear facets according to the dynamic relationship between maxillary and mandibular jaws is a challenging task.[4,13] Occlusal interferences can lead to the reduction of the usual electromyography activity of the masseter muscles and cause temporomandibular disorders.[14,15]

In the conventional fabrication of dental restorations, the shaping of functional occlusal surfaces is especially time-consuming and depends on the experience of the dental laboratory technician.[16] Dental computer-aided design and computer-aided manufacturing (CAD-CAM) technology, introduced to prosthodontics in the 1970s,[17] provides cost-effective production and increased quality and reproducibility.[18,19] Tooth morphology in CAD-CAM can be generated from a library, from mirroring,[20,21] and from copying.[22] As thinner restorations have become popular because of the introduction of materials with improved mechanical properties, it is essential to design restorations with functional occlusal surfaces and reduce the need for occlusal adjustment. The occlusal surface of restorations can be designed to be more functional based on individual mandibular movement parameters and paths.[23] The techniques that the software program delivers are the digitally implemented, functional generated path (FGP) registration[24-26] and the virtual articulator.[27,28] Mandibular movements provide information to eliminate occlusal interferences and to provide physiologic muscle balance.[29]

The FGP record is a "three-dimensional (3D) static expression of dynamic tooth movement."[30] The individual tooth-guided movement paths of the antagonistic occlusal surfaces are engraved as envelope curves. A digitally designed occlusal surface can then be reshaped based on this.[26,31] Disadvantages of the FGP method include that it cannot observe the process of mandibular movement, jaw position, and occlusal contact at the same time.[26] Virtual articulators allow the study of mandibular movement at a specific time, the calculation and visualization of static and kinematic occlusal collisions, and the adjustment of a digitalized occlusal surface to enable collision-free movements.[27,32-34]

Virtual articulators can be divided into mathematically simulated virtual articulators based on existing mechanical articulators and completely adjustable virtual articulators that try to emulate the complex temporomandibular joint (TMJ) system.[27,35-38] The first is capable of reproducing the movements of mechanical articulators and offering different movements in identical settings.[33] Their main disadvantages are that they cannot simulate actual mandibular movement and that all simulated movements are constrained by the structure of mechanical articulators. Casts generally need to be mounted onto a physical articulator and then scanned. Various attempts have been described to align digital casts to virtual articulators directly. Solaberrieta et al[39-41]

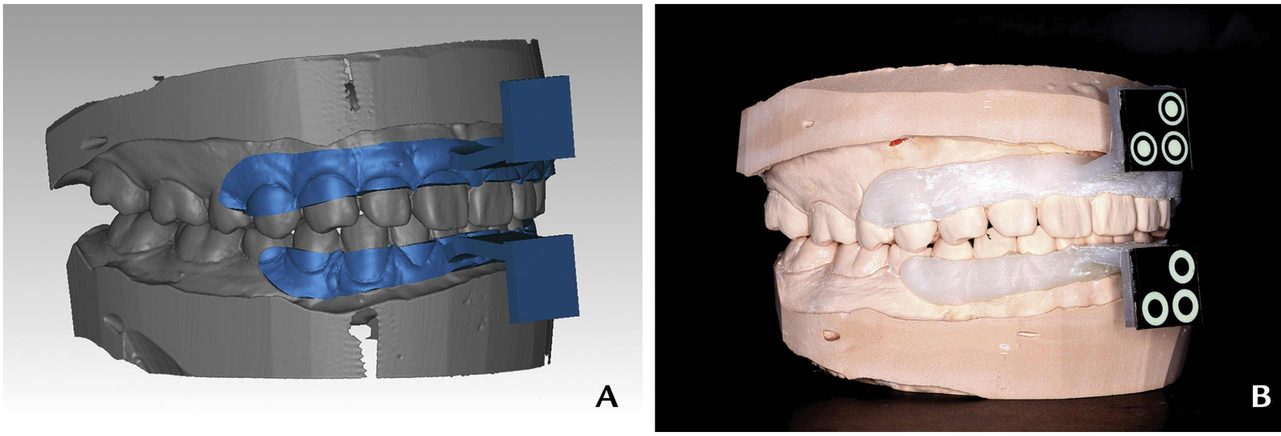

Figure 2. Individual occlusal devices. A, Digital occlusal devices. B, Printed occlusal devices.

and Lam et al[42,43] used a 3D face scanner to orient the digital maxillary jaw to a virtual articulator. However, the face scanner and software program are not readily available in most dental offices and dental laboratories, making this approach hard to implement. Lepidi et al[44] aligned the hinge axis and reference plane of the digital skull to a virtual articulator. However, the anatomic hinge axis of the condyle is not always coincident with the kinematic hinge axis. Another type of virtual articulator combining actual mandibular movement, 3D dentition data, and computed tomography (CT) data or facial 3D data is able to dynamically reproduce the individual jaw movement, which is recorded by various jaw movement–tracking systems.[39,41,45,46] However, the method requires expensive equipment and complex operation, which limits its wide range of application.

To address these problems, a novel virtual articulator system was developed which can record and simulate personalized mandibular movement.[47] The system can record point cloud data of anterior teeth and 3D mandibular trajectories. Additionally, the system supports motion simulation, automatic occluding relation detection, and dynamic occlusal adjustment.[48] The purpose of this clinical study was to establish a clinical application protocol for the novel virtual articulator system and to compare its ability to reproduce the morphology of the occlusal wear facets with a CAD software program (exocad; exocad GmbH) that designed restorations in static and dynamic occlusion (Fig. 1). The null hypothesis was that the morphology of the occlusal wear facets designed by different methods would be similar.

MATERIAL AND METHODS

This clinical study was approved by the Bioethics Committee of Peking University School and the Hospital of Stomatology, PR China (no. PKUSSIRB-201951170). Written informed consent was obtained from each

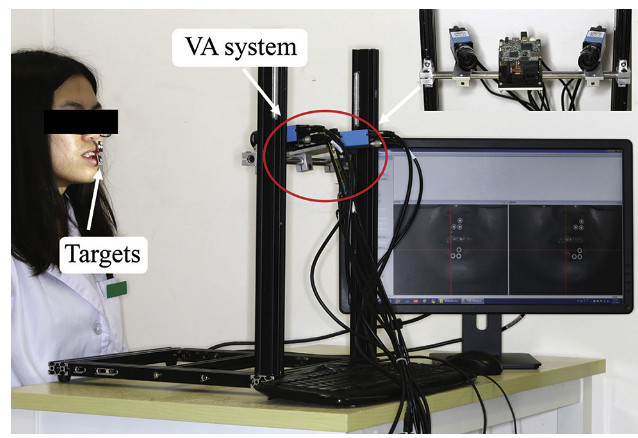

Figure 3. Novel VA system. VA, virtual articulator.

participant. Inclusion criteria required participants to have a complete permanent dentition with intact occlusal surfaces, without active carious lesions, restorations, or other tooth defects and without malocclusion or signs of temporomandibular disorders.

Twelve participants (9 women and 3 men aged from 23 to 28 years and with an average age of 25.6 years) from Peking University School and the Hospital of Stomatology were enrolled in the study. Sample size calculation was based on the mean values of 3D deviation of single crowns by using 1-way analysis of variance (ANOVA). The calculated sample size was 12, based on a significance level of 0.05 and power of 80%. The third molars were not considered in this clinical study.

Mandibular and maxillary impressions and gypsum casts were made and mounted in an articulator (Artex CN; Amann Girrbach AG) in the intercuspal position (ICP) with zero-expansion articulator stone (ZERO arti; Dentona AG). A cast scanner (Activity 880; smart optics Sensortechnik GmbH) was used to scan the cast surfaces and buccal occlusal data in ICP fixed by a transfer device. All data were saved in standard tessellation language

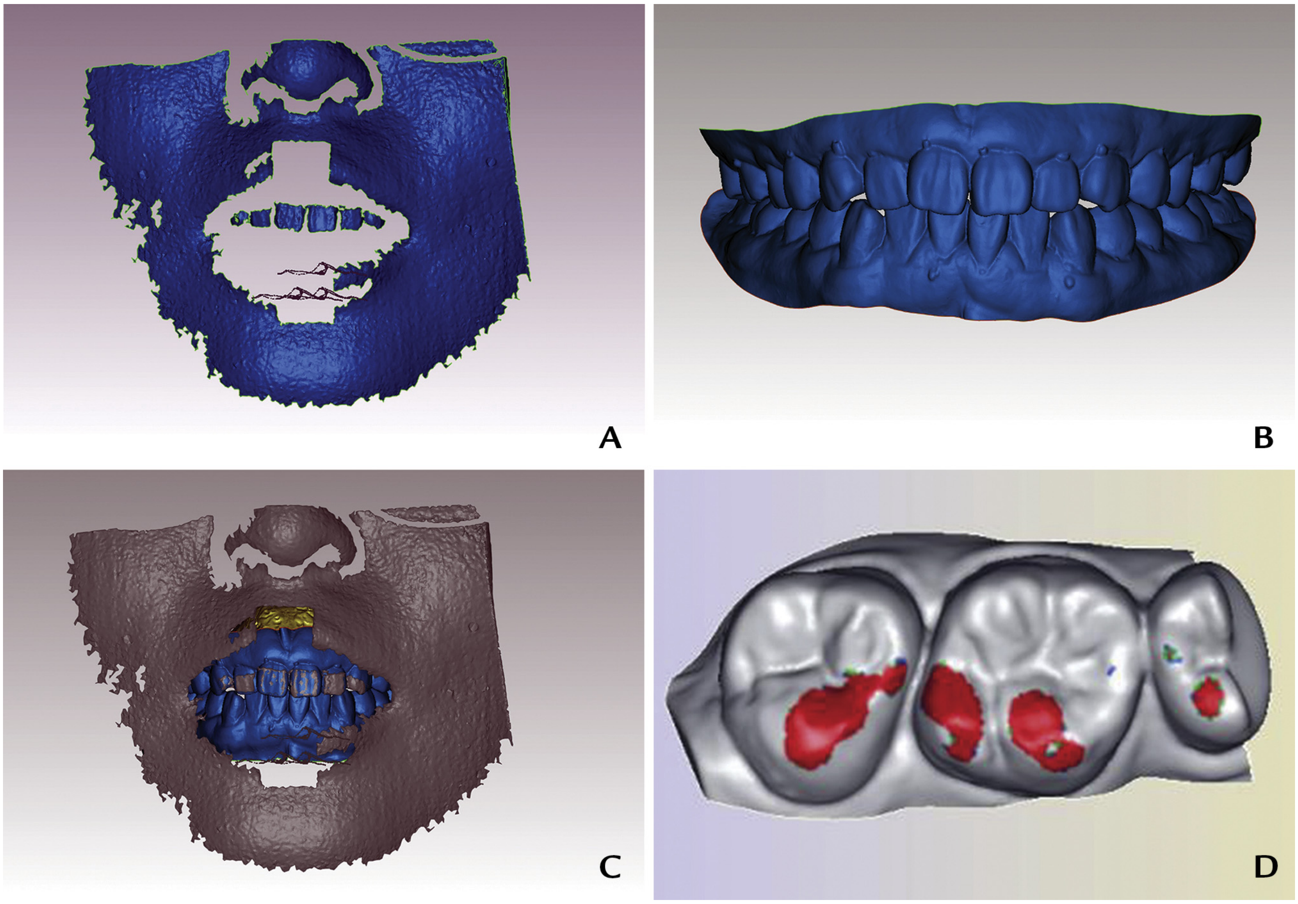

Figure 4. Mandibular movement simulation and collision detection. A, Data obtained by novel virtual articulator. B, Digital casts. C, Alignment of digital casts and wrapped data. D, Collision detection.

(STL) format as the original data after the registration process. The original data were imported into a 3D data-processing software program (Geomagic Studio 2013; 3D Systems Inc) and duplicated for the experimental groups. A single crown (SC), 3-unit splinted crowns (TUC), a 5-unit fixed partial denture (FPD), and a fixed complete denture (FCD) were virtually prepared separately on the digital mandibular casts by using the "Sculpt Knife" tool according to the recommendation for ceramic restorations. The teeth involved in the 4 kinds of restorations were as follows: SC, the first molar; TUC, ipsilateral molars and second premolar; FPD, ranging from the second molar to the ipsilateral canine, in which the first premolar was virtually extracted; FCD, all teeth, in which 4 incisors, first premolars, and the contralateral first molar of SC were virtually extracted.

Wear facets were defined as any wear line or plane on tooth surfaces,[49] characterized by smooth, polished, and usually well-delineated surfaces.[50,51] All wear facets of mandibular teeth were manually marked on the original casts and duplicated along with their casts. The "Sculpt Knife" command was used to form occlusal interferences on the wear facets by means of elevating facets by 0.3 mm in the occlusal direction which will be adjusted afterward by different techniques. Mandibular teeth with occlusal interferences were segmented, and corresponding digital wax patterns were generated.

Individual occlusal devices covering the buccal area of the anterior teeth and premolars of the original digital casts were designed and printed with a 3D printer (Lingtong II; Beijing Shino tech Co, Ltd) (Fig. 2). The devices were fixed on the arches, and the targets characterized by concentric circles were attached to them. By recording the trajectories of circle centers, the movements of both jaws could be obtained, as 3 noncollinear points describe the position of a rigid body in space.[52] The system recorded the 3D cloud data of the maxillofacial surface and anterior teeth and the protrusive and laterotrusive mandibular movements of the participants (Fig. 3) in the same coordinate. The 3D cloud data were wrapped and aligned to the original casts (Fig. 4).

The exocad software program was used to design corresponding restorations with the copy method. The parameters of the built-in virtual articulator were set as follows: Bennett angle=10 degrees, inclination of

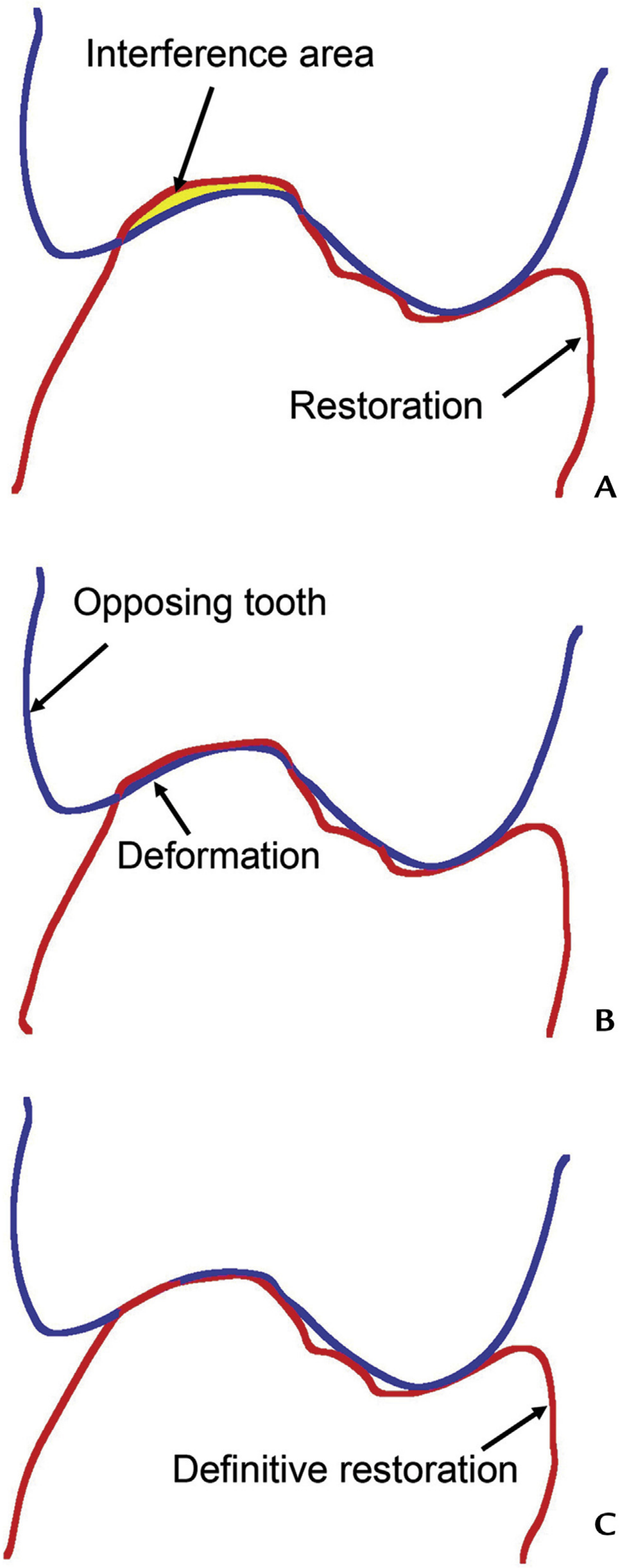

Figure 5. Profile of Laplacian deformation process. A, Occlusal interference detection *(yellow)*. B, Laplacian deformation of restoration. C, Definitive restoration.

laterotrusive condylar guidance=30 degrees, immediate side shift=0.5 mm, and height of incisal guide pin=0 mm. The occlusal surfaces were adapted to antagonists in static occlusion (STA restoration) and in dynamic occlusion simulated by the virtual articulator (DYN restoration).

The self-developed virtual dynamic occlusal adjustment system[52] was used to detect occlusion between digital maxillary casts and wax patterns during mandibular movements (Fig. 4), and the occlusal surfaces were adjusted by Boolean operation and Laplacian deformation for the functional restoration (FUN restoration). The deformation process is shown in Figure 5. The interference intensities were all set to 0 mm for the 3 methods.

The wear facet areas on the original mandibular casts were selected as the reference, and the 3D deviation analysis with the 4 kinds of restorations adjusted by the 3 methods was carried out (Fig. 6). The 3D deviation is the shortest distance from the test object to any point on the reference object. The mean value and root mean square (RMS)[53] estimate were obtained from the following equation:

$$RMS=\sqrt{\frac{\sum_{i=1}^{N}(x_i)^2}{N}},$$

where x_i is the point distance from the restorations to corresponding point i on the original wear facets and N is the total number of points.

The mean value indicates the superiority of positive or negative errors.[54] For basic quantitative analysis, RMS can serve as a measure of how far deviations between 2 different data sets vary from zero.[55] The volumes in the occlusal direction were calculated and defined as positive volumes (V+). V+ indicated that occlusal adjustment is needed to eliminate interferences.

Statistical analysis was performed by using a statistical software program (IBM SPSS Statistics, v19.0; IBM Corp), the Shapiro-Wilk test for normality, and the Levene test for equality of variances. Statistically significant differences were analyzed by using either the 1-way ANOVA followed by the post hoc least significant difference (LSD) test or the Kruskal-Wallis test, depending on the normality (α=.05).

RESULTS

The results of 3D deviation and V+ of the 4 kinds of restorations adjusted by the 3 methods and the original occlusal wear facets are shown in Figure 7, Table 1, and Table 2. The mean 3D deviation values of the 4 kinds of STA restorations ranged from 0.19 mm to 0.22 mm, the DYN restorations from 0.13 mm to 0.17 mm, and the

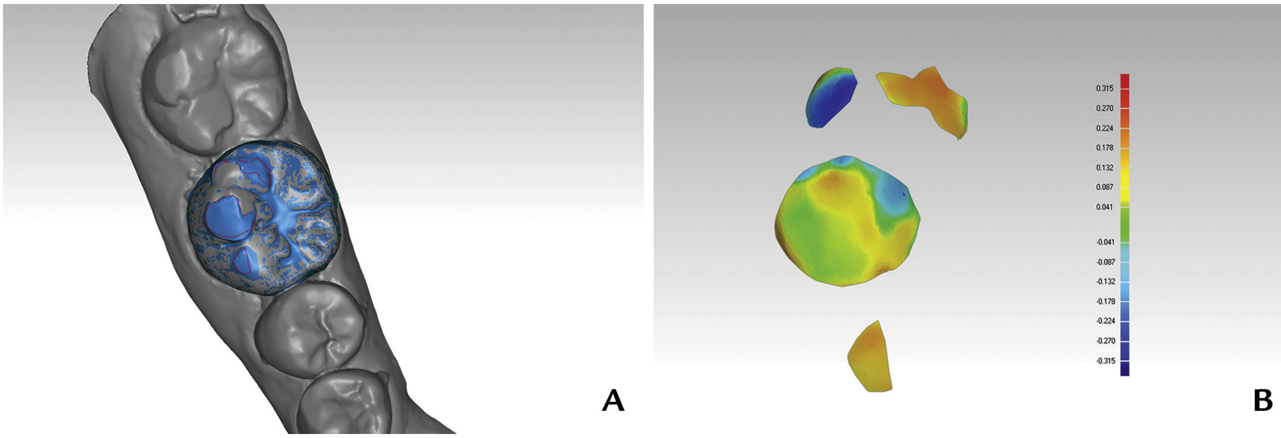

Figure 6. Three-dimensional similarity measurement. A, Restoration. B, Three-dimensional deviation analysis.

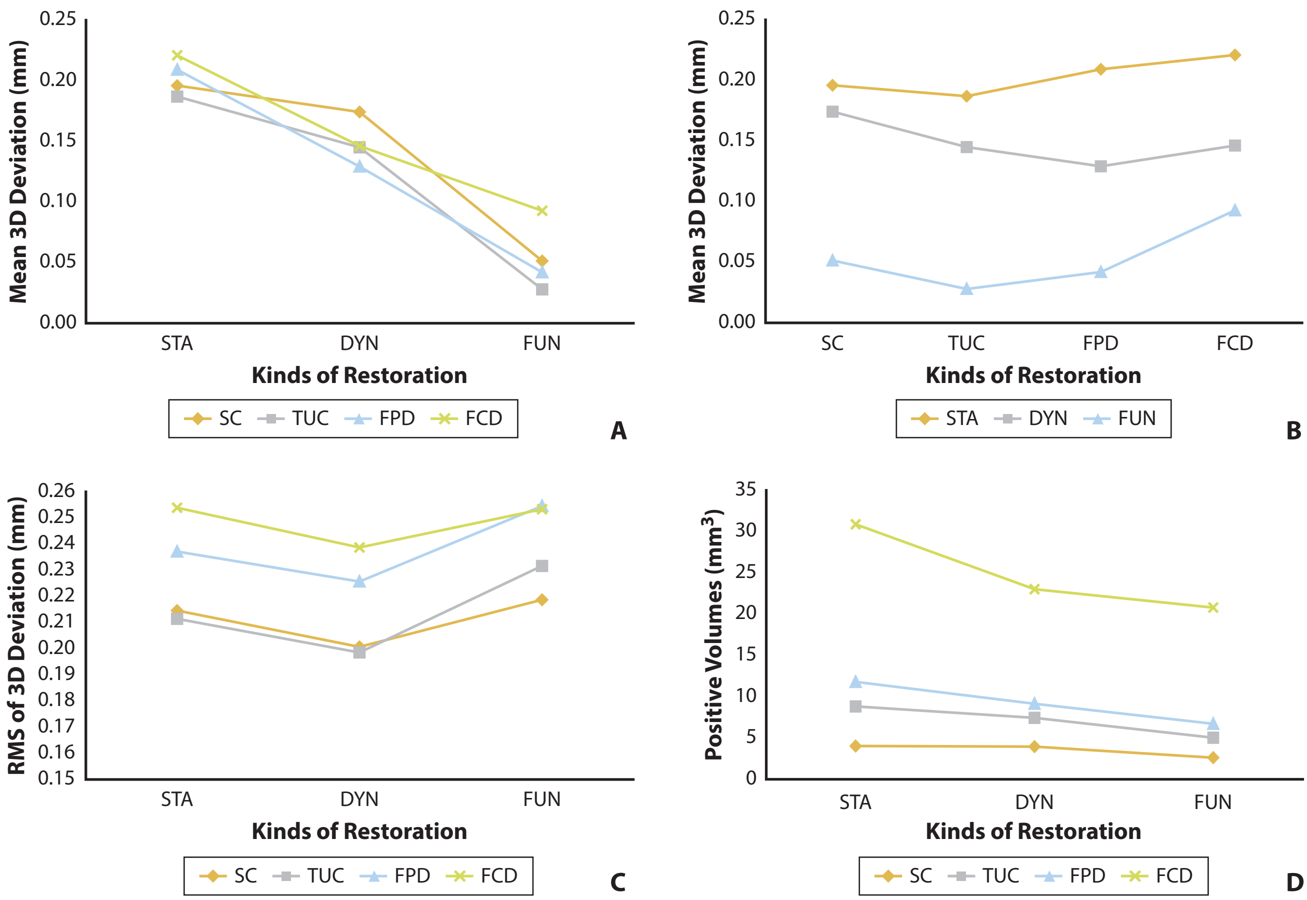

Figure 7. Three-dimensional deviation and positive volumes between restorations and original occlusal wear facets. A and B, Mean values of three-dimensional deviation. C, Root mean square of three-dimensional deviation. D, Positive volumes. DYN, restoration adjusted by virtual articulator with default parameters; FCD, fixed complete denture; FPD, 5-unit fixed partial dentures; FUN, restoration adjusted by individual mandibular movement; SC, single crown; STA, restoration adjusted by static occlusion; TUC, 3-unit splinted crowns.

FUN restorations from 0.03 mm to 0.09 mm. The mean 3D deviation values of FCD and the RMS of TUC, FPD, and FCD were normally distributed with homogeneous variance, and 1-way ANOVA was used for statistical analysis. The Kruskal-Wallis test was used for the others.

The mean values of 3D deviation and V+ decreased from the STA group to the DYN group and then to the FUN group. The difference of mean 3D deviation values between the STA group and the DYN group increased with the increase in the involved number of teeth, and

Table 1. Mean ±standard deviation 3D deviation between restorations and original occlusal wear facets (mm)

Index	Type	STA	DYN	FUN	F	P
Means	SC	0.20 ±0.06	0.17 ±0.07	0.05 ±0.17	—	.057
	TUC	0.19 ±0.07	0.15 ±0.08	0.03 ±0.17	—	.016*
	FPD	0.21 ±0.08	0.13 ±0.09	0.04 ±0.19	—	.025*
	FCD	0.22 ±0.10	0.15 ±0.10	0.09 ±0.19	2.712	.081
RMS	SC	0.21 ±0.06	0.20 ±0.07	0.22 ±0.07	—	.721
	TUC	0.21 ±0.07	0.20 ±0.05	0.23 ±0.05	0.099	.906
	FPD	0.24 ±0.09	0.23 ±0.06	0.26 ±0.08	0.433	.652
	FCD	0.25 ±0.11	0.24 ±0.08	0.25 ±0.09	1.022	.371

DYN, restoration adjusted by virtual articulator with default parameters; FCD, fixed complete denture; FPD, 5-unit fixed partial dentures; FUN, restoration adjusted by individual mandibular movement; RMS, root mean square; SC, single crown; STA, restoration adjusted by static occlusion; TUC, 3-unit splinted crowns. Data listing F-value were analyzed by 1-way ANOVA test and others by Kruskal-Wallis test. *Mean difference significant (*P*<.05).

the difference between the DYN group and the FUN group showed an opposite trend. In terms of the TUC and the FPD, a significant difference of mean 3D deviation values was found between the STA and FUN groups (*P*=.013, *P*=.021). The results are shown in Table 3. The RMS and V+ among the 3 groups were statistically similar (*P*>.05).

DISCUSSION

For single crowns and fixed complete dentures, the results led to acceptance of the null hypothesis. For 3-unit splinted crowns and 5-unit fixed partial dentures, the results led to rejection of the null hypothesis: The occlusal surfaces designed by personalized mandibular movements were more coincident with the morphology of the occlusal wear facets on the original teeth.

In this clinical study, a new virtual articulator system was developed to record and simulate personalized mandibular movement. The system overcame the deficiencies of conventional mechanical articulators. It should allow dentists and dental laboratory technicians to work in a fully digital environment without mounting casts on a physical articulator thereby simplifying the process. It was not necessary to determine the hinge axis or record articulator parameters. Using the system should enable restorations to be designed that articulate with opposing teeth and harmonize with mandibular movements. With further development, it may lead to improved clinical treatment with fixed restorations. Compared with other electronic jaw movement–tracking systems such as JMA (zebris Medical GmbH)[56] and CADIAX (Whip Mix Corp),[57] the system features low cost, a straightforward design, and convenient operation.

The difference of occlusal wear facets of the 4 kinds of restorations adjusted by the 3 methods was studied. The STA restorations may have occlusal interferences because they were designed in static occlusion, and their occlusal surfaces would require adjustment for dynamic occlusion.

Table 2. Mean ±standard deviation V+ between restorations and original occlusal wear facets (mm^3)

Type	STA	DYN	FUN	P*
SC	4.03 ±3.82	3.96 ±3.66	2.62 ±3.02	.320
TUC	8.83 ±7.55	7.43 ±6.55	5.04 ±6.11	.088
FPD	11.80 ±8.26	9.15 ±7.96	6.72 ±7.07	.064
FCD	30.89 ±17.52	23.03 ±15.31	20.80 ±19.00	.209

DYN, restoration adjusted by virtual articulator with default parameters; FCD, fixed complete denture; FPD, 5-unit fixed partial dentures; FUN, restoration adjusted by individual mandibular movement; SC, single crown; STA, restoration adjusted by static occlusion; TUC, 3-unit splinted crowns; V+, volume in gingival direction. *Kruskal-Wallis test.

Table 3. Pairwise comparisons of mean values of 3D deviation among 3 methods of 3-unit splinted crowns and 5-unit fixed partial dentures

Type	Sample 1	Sample 2	Test Statistic	Std. Error	P[a]
TUC	STA	DYN	4.750	4.301	.808
	STA	FUN	12.250	4.301	.013[b]
	DYN	FUN	7.500	4.301	.244
FPD	STA	DYN	-28.667	6.898	.287
	STA	FUN	-5.208	6.898	.021[b]
	DYN	FUN	-10.542	6.898	.913

DYN, restoration adjusted by virtual articulator with default parameters; FPD, 5-unit fixed partial dentures; FUN, restoration adjusted by individual mandibular movement; STA, restoration adjusted by static occlusion; TUC, 3-unit splinted crowns. [a]Pairwise comparisons. [b]Mean difference significant (*P*<.05).

The virtual articulators of the exocad software program provided important additional information for occlusal design; consequently, the mean 3D deviation values of the DYN restorations decreased compared with those of the STA restorations. However, the average-value articulation does not represent actual patient movements, especially when there are not enough unprepared teeth to constrain the paths which are influenced by tooth contacts. Fortunately, the simulation of personalized mandibular movement was similar to the actual occlusion, and the FUN restorations can better match the original wear facet morphology.

In theory, the FUN restorations should fit with the static and dynamic occlusions of the participants. However, in some situations, cumulative errors can lead to unsatisfactory occlusal surfaces. The results of collision detection during the simulation of personalized mandibular movements were not always coincident with intraoral actual conditions because of gypsum expansion, impression defects, tooth mobility, or mandibular deformation under loading.[58-61] Mühlemann[62] reported that natural teeth can move 40 to 120 μm in the horizontal direction when loaded with a 4.9-N force. Kim et al[63] indicated teeth can move 25 to 100 μm in the axial direction. However, gypsum casts cannot simulate the physiological changes of the stomatognathic system. Future research should consider mandibular deformation and tooth mobility to produce a virtual patient module. Additionally, the accuracy should be improved to ensure the design of collision-free and functional restorations.

CONCLUSIONS

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

1. The novel virtual articulator system can be used to record and simulate actual mandibular movement.
2. The system can detect dynamic occlusal collision and adjust the occlusal surfaces of restorations without the constraints of articulator parameters.
3. The FUN restorations were better matched to the morphology of the occlusal wear facets on the original teeth than those on the STA and DYN restorations designed by the virtual articulator of the exocad software program.

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Noteworthy Abstracts of the Current Literature

Performance of PEEK based telescopic crowns, a comparative study

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Objective. Telescopic crowns are suitable components of partial dentures to efficiently anchor dental supra-structures to teeth or dental implants and achieve high chewing performance and wear comfort. Usually alloy- or metal-based structures are used for the primary and the secondary crowns. The advantage is the possibility to produce precise structures with a high perfection and sufficient friction force, but the disadvantage is the corrosion instability. The recent introduction of zirconia ceramics has enabled the fabrication of ceramic primary crowns, thus reducing corrodibility. The novel application of the high-performance polymer polyetheretherketone (PEEK) as another metal-free alternative material offers a new perspective for such applications. Therefore, the aim of this work was to assess the performance of telescopic crowns of PEEK by comparing telescopic crowns based on the combination of PEEK (prim. crown)+PEEK (sec. crown) with the pairings ZrO_2 (prim. crown)+PEEK (sec. crown) and CoCr-alloy (prim. crown)+PEEK (sec. crown).

Methods. All specimens were CAD/CAM planned and manufactured based on a model of a tooth 26. One master dental technician performed the post-treatment. For each group of material pairing, n=9 telescopic crown pairs were manufactured and tested. Herein not only the maximum retention force was measured but also the retention force vs. pull-off distance were analyzed. As there is no commonly accepted test protocol available, the influence of various pull off speeds were tested as well. All measurements were first made with three blocks of three crowns (3C), subsequently with three blocks of two crowns (2C) and finally with nine single crowns (1C). The long-term behavior was estimated by performing 10.000 cycles, which is related to a lifetime of more than 10 years.

Results. The maximum retention force in case of PEEK+PEEK was higher in comparison to the other tested material pairings. In the range between 1 and 10 mm/ min pull off speed there was no significant influence by the pull off speed. More influence on the friction force would be expected by changes of the number of the crowns acting simultaneously. The friction force was decreasing with decreasing number of crowns but not linearly in any tested case. The long-term test has shown that the friction force remained constant.

Significance. The performance of PEEK+PEEK telescopes is comparable with the usually applied material pairings. Over long time no loss in retention force could be observed. The retention force - distance progression in the PEEK+PEEK pairing offers more security against a possible loss of retention during repair or relining. For further tests of the performance of telescopic crowns or to estimate of friction force limits, a setup with at least two, but preferably three, crowns tested in parallel is suggested.