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Construction of virtual intercuspal occlusion: Considering tooth displacement

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Abstract

Common impressions cannot accurately duplicate the dental occlusion under occlusal force due to tooth displacement and mandibular deformation. To establish new methods to construct virtual intercuspal occlusion and assess their construction accuracy. The intraoral occlusal contacts of posterior teeth of 15 subjects were recorded with 8 μm and 100 μm articulating paper, respectively, and the marked teeth and buccal bite data were scanned with an intraoral scanner. The virtual dental occlusions were separately determined by buccal bite registration (BBR) method, and 3 new methods, namely segmented tooth registration (STR), occlusal contact areas (marked by 8 μm articulating paper) registration (OCR) and mixing registration (MR) methods. With the intraoral contact areas marked by 100 μm articulating paper set as reference and contact areas of the 4 virtual occlusions as tests, sensitivity, positive predictive value (PPV) and the ratio of overlapping areas were calculated. Kruskal-Wallis test or 1-way ANOVA was used to analyse the difference among groups. The sensitivity ranged from 0.69 to 0.94 and the PPV from 0.67 to 0.90. Sensitivity of OCR group and PPV of STR and OCR groups were different from that of BBR group at overlapping threshold of 50% ($P = .028$, .028 and .006). There was statistical difference of the ratio of overlapping areas over reference areas, and the values of STR and OCR groups were higher than that of BBR group ($P = .045$ and .021). The ability of STR and OCR methods to construct virtual intercuspal occlusion was better than BBR method.

KEYWORDS

dental occlusion, intercuspal occlusion, intraoral scanner, occlusal contact, tooth displacement

1 | INTRODUCTION

Accurately duplicating the patient's dental occlusion has a significant influence on the occlusion analysis and occlusal design of the restorations. The inaccuracy and deficiency of dental occlusion may result in failure of treatment.[1]

In traditional clinic, wax, silicone rubber and other occlusal recording materials are used to transfer the occlusal relationship between opposing dentition arches.[2] However, for beginners with no enough clinical experience, the technique is difficult to master.

The introduction of intraoral scanner (IOS) systems has led to the realisation of a fully digitised and model-free workflow. With the improvement of scanner resolution and the application of colour IOSs, three-dimensional (3D) morphology of the tooth, along with a photorealistic copy of the tooth colour can be obtained simultaneously. The static interocclusal relationship is registered intraorally via scanning the buccal bite portion with the maxillary and mandibular teeth in intercuspal position (ICP). The method

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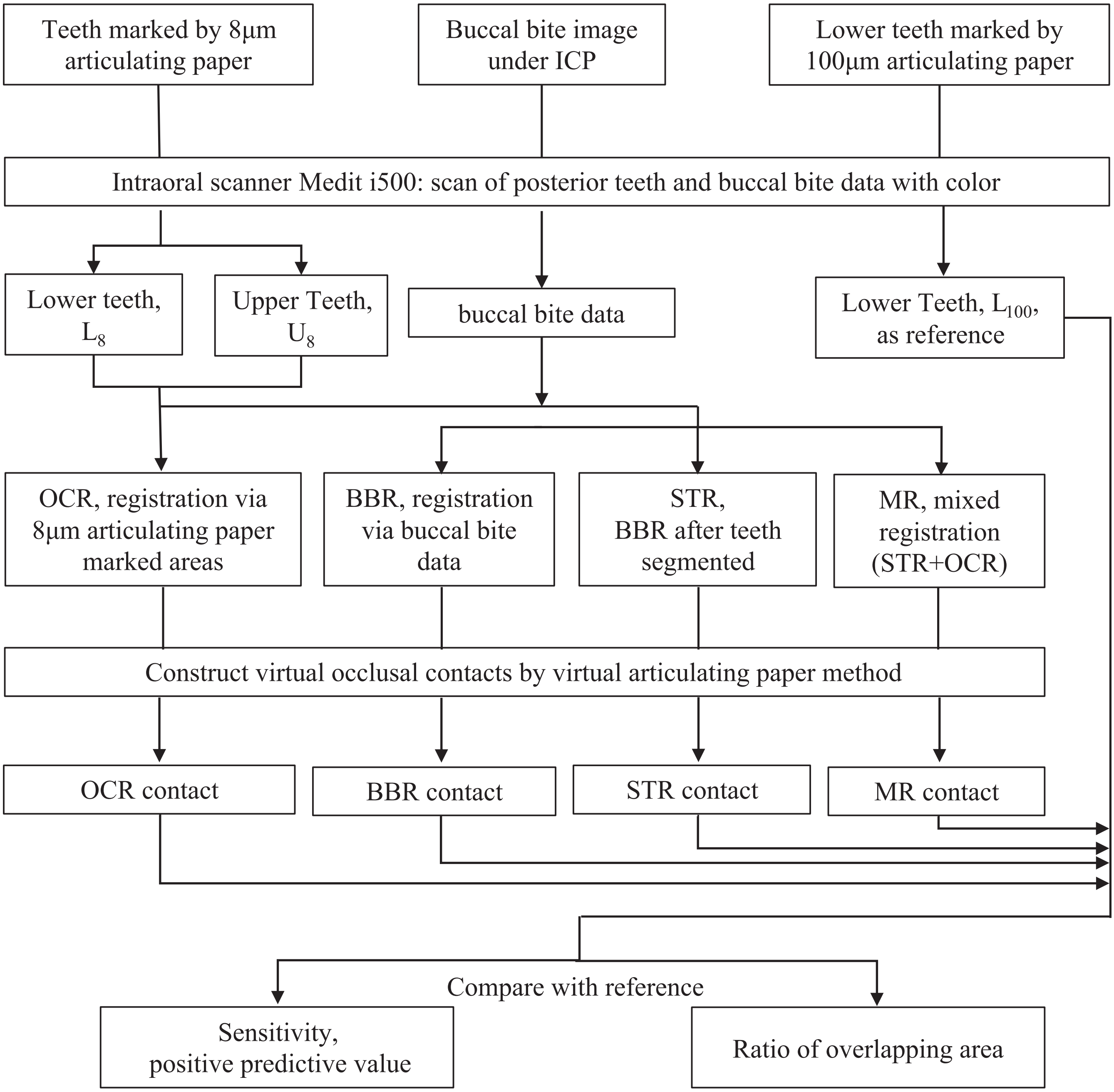


FIGURE 1 Flowchart of study protocol

illustrates occlusal contacts in different colours and offers useful information in the analysis of occlusion without the need of any impression materials.[1,3] However, there are still some limitations in the buccal bite registration (BBR) method by the software programme of IOSs. The IOSs allow penetration. If the penetration is corrected, the reliability will be reduced and occlusal areas will change.[4-6] The physical tooth displacement[7-9] and dental arch deformation[10-12] under occlusal bite force are not taken into account and maybe the reason for the penetration phenomenon. Non-rigidity of the bone and periodontal ligament allows minor tooth movement during forceful tooth clenching[13,14] and the deformation of mandible under the influence of masticatory muscle forces.[15,16] As a result, the spatial position and tilt angle of every tooth would change under bite force and it has been confirmed by various researches. Gomes, DOS,[9] Oh, SH,[17] Saad, MN[18] and Komiyama, O et al[19] indicated that the teeth were displaced under bite force by measuring the proximal contact tightness and the number of occlusal contacts.

For IOSs to be used more generally, it must be able to obtain precise 3D position of the dentition, and the virtual occlusion that results from those images must be able to reproduce the actual occlusion.[3] Taking tooth displacement into account during the construction of dental occlusion, the validity of occlusal contacts obtained by IOSs will be improved.

The purpose of this study was to establish new 3D construction methods of virtual intercuspal occlusion by using buccal bite data and intraoral occlusal contacts based on the current BBR method and assess their construction ability by comparing virtual and intraoral occlusal contacts. The null hypotheses of the study were that buccal bite registration, segmented tooth registration, occlusal contact areas (marked by 8 μm articulating paper) registration and mixing registration methods would construct virtual intercuspal occlusion with similar location, count and area of contacts.

2 | MATERIALS AND METHODS

This research has been approved by the Bioethics Committee of Peking University School and the Hospital of Stomatology, China (PKUSSIRB-201951170). The sample size was calculated based on a significance level of 0.05 and power of 80%.

Fifteen postgraduates (10 women and 5 men aged from 22 to 30 years and with an average age of 25.7 years) were recruited from the Peking University School and Hospital of Stomatology. Written informed consent was obtained from each subject. Inclusion criteria for this clinical study were as follows: complete permanent dentition except for the third molars, sound periodontium and teeth on at least one side, stable occlusion with an Angle Class I occlusal relationship, normal mouth opening degree, multi-point contact of molars, without dental crowding, signs of temporomandibular dysfunction, craniomandibular disorders or orthodontic therapy. Subjects with signs of malocclusion such as angle class II or III or unilateral/bilateral crossbite were excluded from the study. The whole flowchart of study protocol was shown in Figure 1.

2.1 | Scanning of intraoral occlusal contacts and digital casts

Various factors may affect the maximum bite force,[20] and pain may limit the maximum bite force due to reflex mechanisms.[21] During chewing of ordinary food, the voluntary force capacity of the jaw-closing muscles and the transient force-withstanding capacity of the periodontal tissues are only partly utilised. The total chewing and swallowing force were obviously lower than the total maximum bite force in habitual occlusion, along with great individual variations.[22] Therefore, the subjects were guided to practice the process of habitual tapping movement and bite in ICP under normal bite force repeatedly. The bite force was not maintained to a uniform value among subjects, but the most accustomed force that the individual felt, which is commonly used for clinical interocclusal recording and occlusal adjustment. Articulating paper (8 μm, Arti-Fol BK 25 Red; Dr Jean Bausch, Germany) was used to mark occlusal contacts 3 times. The results were assessed by an expert with 20 years of clinical experience. If the occlusal contacts were consistent visually, the bite force was considered to be repeated steadily.

During the examination, subjects comfortably seated upright in a dental chair with the head supported. Identification of intraoral occlusal contacts in ICP under the same bite force as guided beforehand was performed with 8 μm articulating paper after drying the teeth surface. The IOS i500 (v2.0.3, Medit Corp.) was used to scan the marked maxillary and mandibular posterior segments (U_8 and L_8, ranging from the first premolar to ipsilateral second molar and the maxillary canine also included whether having contact with the mandibular first premolar) under open-mouth state, which is able to record 3D surface data with colour. The scans were performed by an experienced user, who had accepted prior training sessions before conducting the scans. By scanning the buccal bite when the two arches were in ICP, the IOS immediately reproduced the occlusal state of the digital casts, and here this method was called after BBR method. The posterior dentition data and buccal bite data after registration process were saved in polygon file format. The marked occlusal surfaces were wiped with an alcohol cotton ball and dried. Another articulating paper (100 μm, Arti-Fol BK52 Red; Dr Jean Bausch, Germany) was used to record occlusal contacts, which were set as reference, and the mandibular posterior segments (L_{100}) were scanned again. Subjects were asked to keep the same bite force during the occlusal contact recording process and buccal bite data scanning process. 28 pairs of digital casts were obtained, for 2 of these 15 subjects were analysed only for right side posterior segment while other 13 subjected were recorded for both sides. Arrested caries occurred on the left side posterior segments of 1 subjects and the data was not included. Another subject withdrew content and cannot cooperate with the scanning of the left side posterior segment due to his own schedule.

2.2 | Construction of virtual dental occlusion and virtual occlusal contacts

The digital data were imported into 3D data processing software programme (Geomagic Studio 2013; 3D Systems Inc). The boundaries of occlusal contacts according to the colour information were created to determine the intraorally marked occlusal contact areas of the maxillary and mandibular teeth. Data L_{100} was aligned to test models L_8 by the manual registration and 'Best Fit Alignment' command successively. The intraorally marked occlusal contact boundaries of data L_{100} were projected on the data L_8. So, the teeth of L_8 also owned the boundaries of intraoral occlusal contacts marked by 100 μm articulating paper which were set as the reference (Figure 2). The data L_8 along with two set of boundaries were duplicated and used to carry out the process of teeth segmentation and construction of virtual dental occlusion.

In this research, 4 methods were used to register the relationship of maxillary and mandibular dentitions. (a) BBR as described in section 2.1. (b) Segmented tooth registration (STR): Draw the boundaries along the gingival margins and the adjacencies of the crowns, and segment the maxillary and mandibular casts into single tooth (Figure 3A). Establish the teeth part of the buccal bite data by

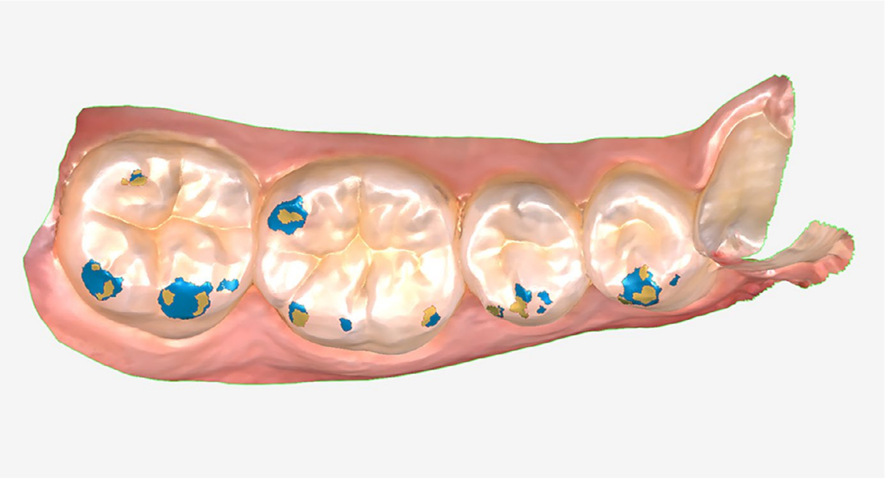


FIGURE 2 Intraoral occlusal contacts marked by 8 μm (yellow parts) and 100 μm (blue parts, reference) articulating paper [Colour figure can be viewed at wileyonlinelibrary.com]

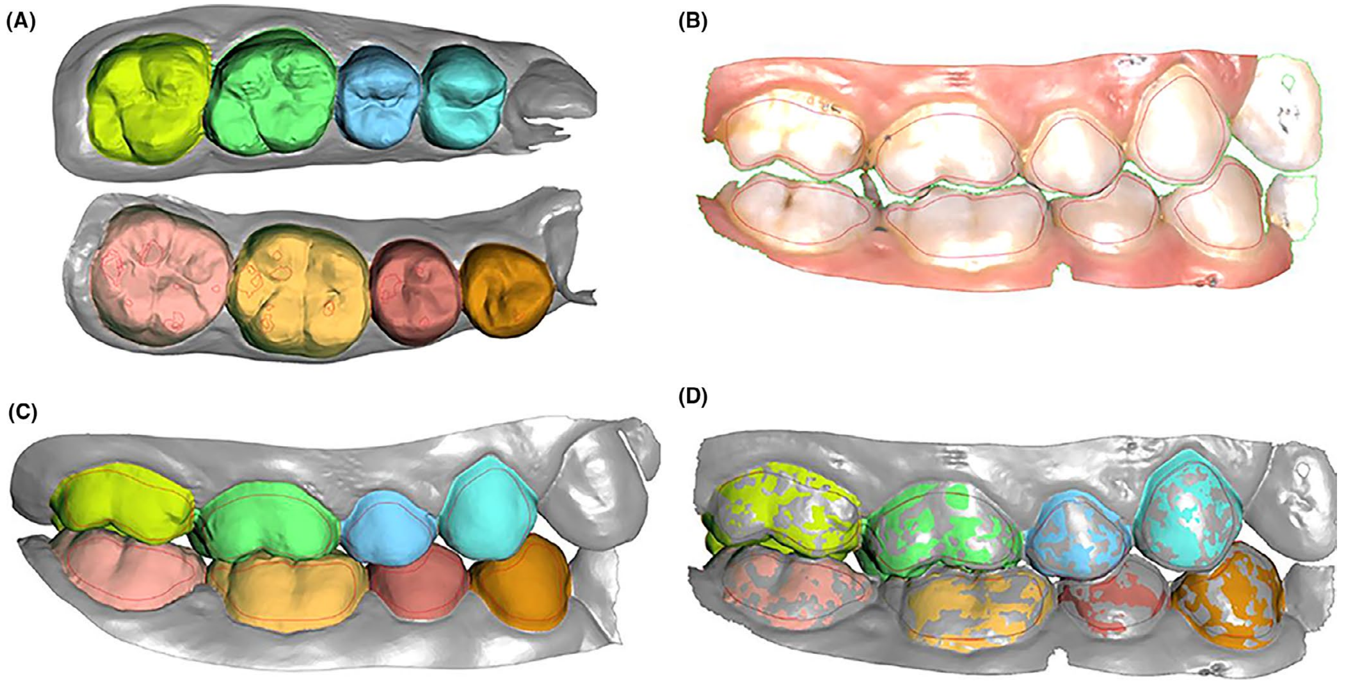
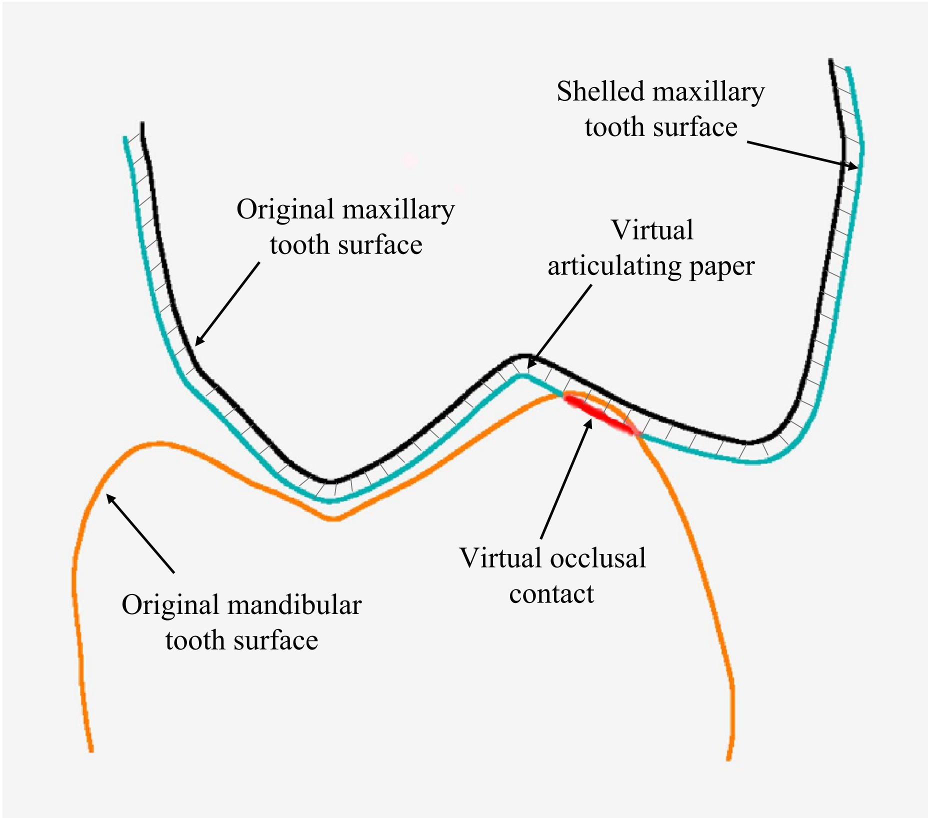


FIGURE 3 Segmented tooth registration method. A, Casts segmented into single tooth; B, Boundaries of the buccal bite data; C, Boundaries projected on single tooth; D, Single tooth registered to buccal bite data respectively [Colour figure can be viewed at wileyonlinelibrary.com]

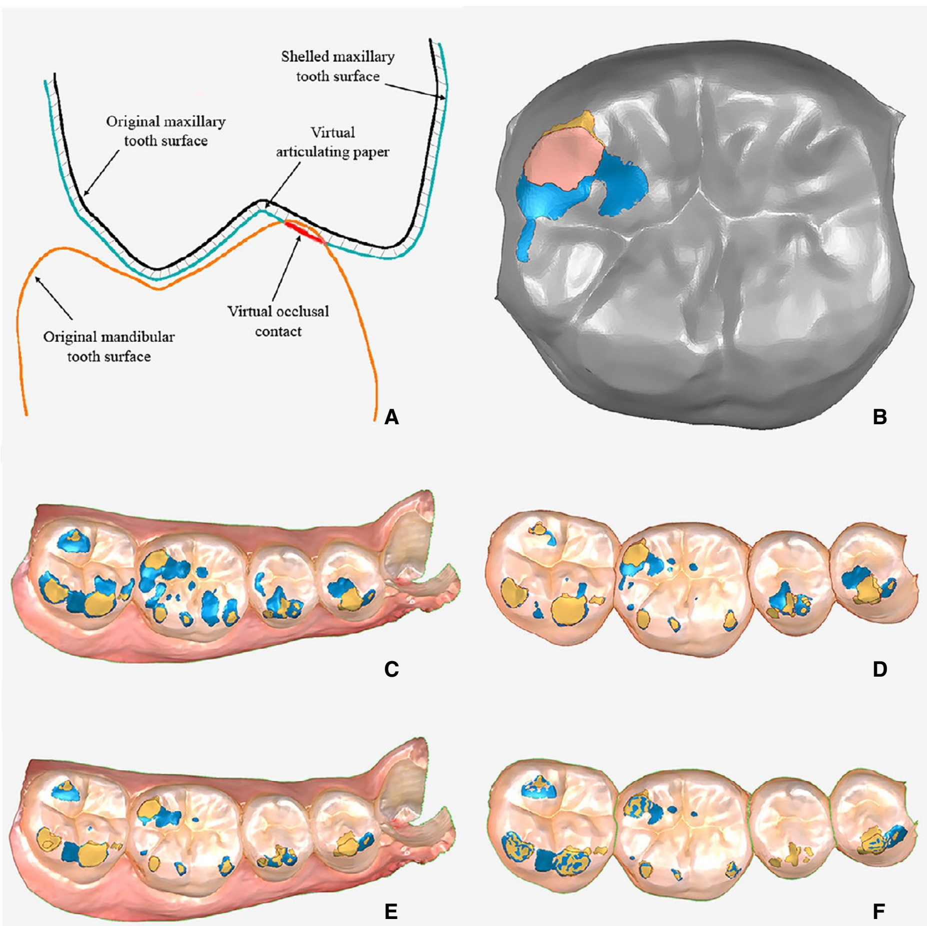
boundaries and project the boundaries on the maxillary and mandibular single tooth to determine the buccal common area of these data (Figure 3B,C). The single tooth was registered to buccal bite data respectively through the 'Best Fit Alignment' function according to the common area (Figure 3D), and the data were saved as new casts. For the convenience of description, we represent this process by the 'segmented tooth registration (STR) method. The process was carried out triplicate, and the average value was used as measurement for each specimen. (c) Occlusal contact areas registration (OCR): Reverse the normal of L_8 and select the occlusal contact areas of both arches marked by 8 μm articulating paper (U_8, L_8). Align the L_8 cast with the U_8 cast using the 'Best Fit Alignment' command to construct the dental occlusion, which named 'occlusal contact areas registration' (OCR) method. (d) Mixed registration (MR): Construct the dental occlusion by the STR method and then by the OCR method, called after 'mixed registration' (MR) method.

FIGURE 4 Virtual occlusal contact and overlapping area. A, Virtual occlusal contact (red) calculated by virtual articulating paper method; B, Overlapping area. Intraoral occlusal contact marked by 100 μm articulating paper (L_{100}, yellow + red), virtual occlusal contact (blue + red), overlapping area (red); C and F, virtual occlusal contacts (blue) of BBR, STR, OCR and MR vs intraoral occlusal contact (L_{100}, yellow). BBR, buccal bite registration; STR, segmented tooth registration; OCR, occlusal contact areas (marked by 8 μm articulating paper) registration; MR, mixed registration [Colour figure can be viewed at wileyonlinelibrary.com]

(A)


Shelled maxillary tooth surface
Original maxillary tooth surface
Virtual articulating paper
Original mandibular tooth surface
Virtual occlusal contact

(B)


Shelled maxillary tooth surface
Original maxillary tooth surface
Virtual articulating paper
Virtual occlusal contact
Original mandibular tooth surface
A
B
C
D
E
F

Virtual articulating paper method was used to determine virtual occlusal contacts. For a pair of aligned maxillary and mandibular dentition, the maxillary cast was offset 100 μm along the normal to form shelled surface of the cast. The hollow part between the original and shelled surfaces was regarded as virtual articulating paper, the thickness of which was also 100 μm, as same as the physical articulating paper. Boolean subtraction operation was used to calculate the intersected area between mandibular cast surface and the front surface of virtual articulating paper that is the shelled surface of maxillary cast. The intersected area was set as virtual occlusal contacts (Figure 4A).

2.3 | Sensitivity, PPV, ratio of overlapping areas

Evaluation of the differences between the virtual contacts calculated from the virtual casts and standard contacts requires quantitative measures, including the location, count, and area and the forces applied at these contacts. The standard occlusal contacts were mostly recorded by articulating paper of different thickness. The indexes of sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV), centroid and normal of occlusal contact were used to indicate occlusal contact location and count. Meanwhile, the ratio of overlap of contact areas was used to show the contact size. Sensitivity indicates the ability of a test to pick up the presence of standard occlusal contacts and PPV refers to probability of contact truly exists when diagnostic test is positive. Overlap is the ratio of overlap of the virtual contact areas compared with the reference. The closer the result of the 3 indexes are to 1, the better.[23-29]

Four set of virtual maxillomandibular relationships and virtual occlusal contacts were obtained. Apart from the intraoral occlusal contacts marked by 8 and 100 μm articulating papers, the mandibular teeth from the origin data L_8 also possessed 1 set of virtual occlusal contacts of corresponding registration method (as test). The test area and the overlap area A_s compared with the corresponding single reference area A_{sioc}, and the ratio of overlap R_s were calculated (Figure 4B).

$R_s = A_s / A_{sioc}$.

Setting the ratio of overlap of 0 to 50% with the interval of 10% as the threshold value, the coincident count of virtual occlusal contacts was measured which overlapping the reference contact with ratio equal or larger than threshold value. Where there was no overlap between virtual and intraoral occlusal contacts, the contacts present in the same cusp or cusp slope were considered as coincident. Then the sensitivity and PPV of the virtual occlusal contacts were calculated with different threshold values.

Sensitivity = TP/(TP + FN).

PPV = TP/(TP + FP).

Where TP is the abbreviation of true positives and refers to occlusal contacts appearing on both reference and test. FN is false negatives and means occlusal contacts appearing only on the reference not the test. FP is false positives and means occlusal contacts appearing only on the test.

The total area of virtual occlusal contacts A_{voc}, total intraoral occlusal contacts A_{ioc} and overlapping area A were counted (Figure 4C-F). To evaluate the accuracy of the virtual occlusal contact areas, the whole ratio of overlap R_i was determined:

$R_i = A/A_{ioc}$

The ratio of overlap R_v and R_u were used to assess whether the virtual occlusal contacts would cause false-positive results.

$R_v = A/A_{voc}$

$R_u = A/(A_{ioc} + A_{voc} - A)$

The same operator conducted all procedures and assessments.

2.4 | Statistical analysis

Statistical analysis was performed by using a statistical software programme (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 analysed 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 ($\alpha = 0.05$).

3 | RESULTS

The sensitivity and PPV of the 4 virtual occlusal contacts were depicted in Figure 5 and Table 1. The sensitivity of the 4 virtual occlusal contacts ranged from 0.69 to 0.94 and the PPV from 0.67 to 0.90. The sensitivity and PPV values decreased with the increase in the threshold value. The whole ratio of overlapping areas of occlusal contacts was shown in Table 1. The R_i of the 4 virtual occlusal contacts ranged from 0.65 to 0.76, the R_v from 0.57 to 0.61 and R_u from 0.43 to 0.47. The PPV with ratio of overlap of 20% to 50% as the threshold value and the R_v and the R_u were with normal distribution and homogeneity of variance, and thus 1-way ANOVA with post hoc LSD test was conducted to compare the difference among groups. Others did not conform to the normal distribution, and Kruskal-Wallis test was selected. With the ratio of overlapping areas of 50% as the threshold value, sensitivity of OCR group was different from that of BBR group ($P = .028$), and PPV of STR and OCR groups were different from that of BBR group ($P = .028$, $P = .006$). There was statistical difference among the ratio of overlapping areas R_i of the STR and OCR groups and that of the BBR group ($P = .045$, $P = .021$). The results of STR and OCR groups were higher than that of BBR group.

4 | DISCUSSION

The results led to partial rejection of the null hypothesis: the STR and OCR methods can construct the virtual intercuspal occlusion with better location, count and area of contacts than BBR method.

When the threshold was set to be 0 to 40%, there was no statistical difference among the 4 virtual occlusion in terms of contact

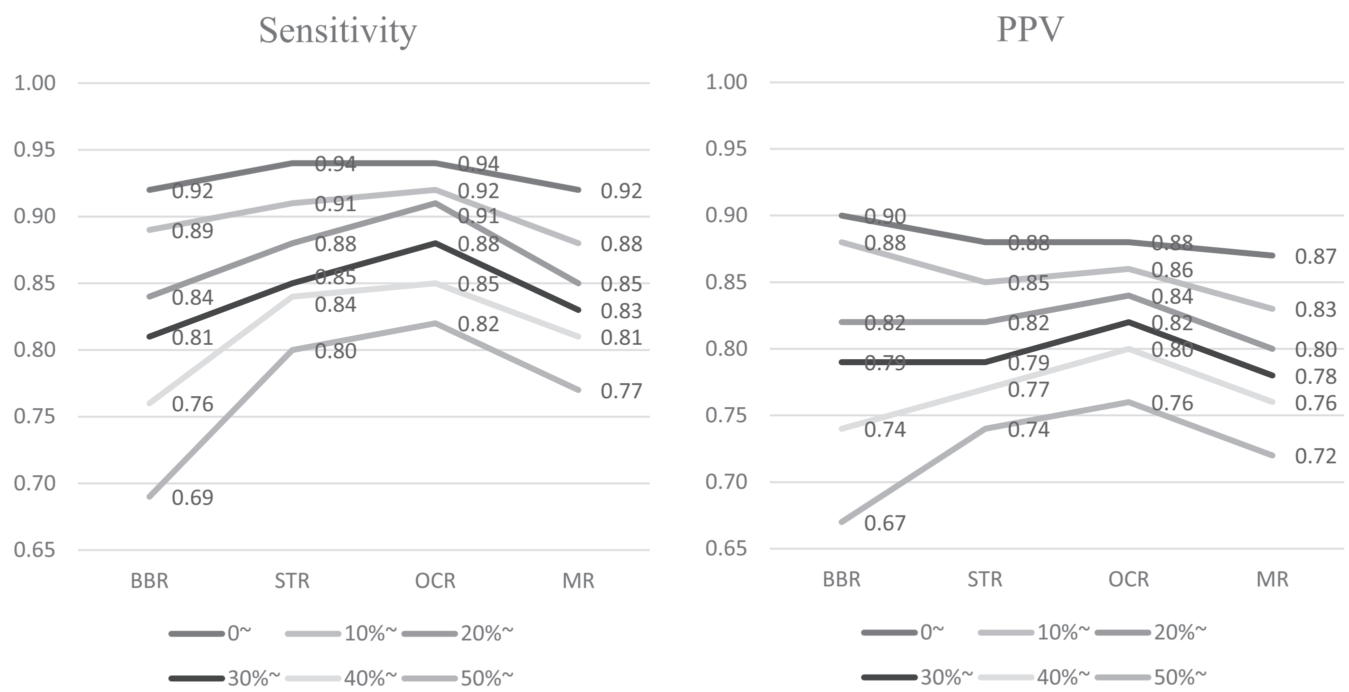


FIGURE 5 Sensitivity and PPV of four virtual occlusal contacts. BBR, buccal bite registration; STR, segmented tooth registration; OCR, occlusal contact areas (marked by 8 μm articulating paper) registration; MR, mixed registration; 0~- 50%~, threshold value, ratio of overlapping areas of single virtual occlusal contact; PPV, positive predictive value

location and count. The sensitivity of virtual occlusal contacts of 4 virtual dental occlusion were all greater than 0.70 and meet the clinical requirements for Ogawa, T,[30] Delong, R[23] and other scholars all proposed that the sensitivity above 0.70 could meet the clinical requirements and later researches mostly followed the recommendation. When the threshold set to be 50%, that is, if only the virtual

TABLE 1 Sensitivity, PPV and whole ratio of overlapping areas of virtual occlusal contacts

Index	Threshold	BBR	STR	OCR	MR	*F*	*P*-value
Sensitivity	0~	0.92	0.94	0.94	0.92	-	.492
	10%~	0.89	0.91	0.92	0.88	-	.436
	20%~	0.84	0.88	0.91	0.85	-	.132
	30%~	0.81	0.85	0.88	0.83	-	.099
	40%~	0.76	0.84	0.85	0.81	-	.067
	50%~	0.69†	0.8	0.82†	0.77	-	.023*
PPV	0~	0.9	0.88	0.88	0.87	-	.698
	10%~	0.88	0.85	0.86	0.83	-	.467
	20%~	0.82	0.82	0.84	0.8	0.770	.513
	30%~	0.79	0.79	0.82	0.78	0.816	.487
	40%~	0.74	0.77	0.8	0.76	1.016	.389
	50%~	0.67†,‡	0.74†	0.76‡	0.72	2.905	.038*
R_i	-	0.65†,‡	0.74†	0.76‡	0.72	-	.015*
R_v	-	0.61	0.57	0.58	0.57	0.364	.779
R_u	-	0.43	0.45	0.47	0.44	0.874	.457

Note: Abbreviations: 0 ~ to 50%~, ratio of overlapping areas of single virtual occlusal contact; BBR, buccal bite registration; MR, mixed registration;OCR, occlusal contact areas (marked by 8 μm articulating paper) registration; PPV, positive predictive value. R_i, R_v and R_u, the ratio of overlapping areas in intraoral occlusal contacts, in virtual occlusal contacts and in union of intraoral and virtual occlusal contacts; STR, segmented tooth registration.

The data listing *F*-value were analysed by 1-way ANOVA test and others by Kruskal-Wallis test. The same footnote †,‡show the significant differences. *Mean difference significant ($P < .05$).

occlusal contacts with overlap ratio of 50% or more were defined as the predicted occlusal contacts, the sensitivity of BBR group could not meet the clinical requirements. In addition, the sensitivity of STR group, and the PPV of STR and OCR groups were superior to that of BBR group. This indicated that the STR and OCR methods can pick up the intraoral contacts and meanwhile ensure lower false-positive results. In case of the whole ratio of overlapping areas of virtual occlusal contacts was analysed, the accuracy of STR and OCR methods to predict the occlusal contact areas were better than that of the BBR method. And simultaneously no redundant false-positive occlusal contact was generated compared with the BBR method.

In dental practice, articulating paper has been established as the most commonly used diagnostic tool.[27] Bausch articulating paper was used in this study and 3D occlusal markings were scanned by an IOS. In order to avoid the error caused by the accuracy of IOS, we set the occlusal contact areas recorded by 100 μm articulating paper as the reference, which is one order of magnitude higher than the IOS accuracy.

In the present study, anterior teeth were not included, because the anterior labial images especially mandibular anterior teeth, with only scant morphological information, cannot supply adequate information for the registration of the single tooth.[3] For short-span areas such as single tooth areas and partial-arch areas, direct digital impressions have been demonstrated to perform within the same accuracy range as conventional impressions with high-precision materials.[31,32] For long-span areas such as complete-arch, it has been reported that there is a need for improvement of IOSs to reach the accuracy levels of conventional impressions.[33-35] These deviations might be related to incorrect superimposition processes of the captured data during processing and a tilting effect towards the site of the interocclusal registration scan.[36-38] Therefore, only unilateral posterior teeth were scanned to ensure the scanning accuracy.

Scholars studied the reliability of subjective judgement of bite force. Chen, YH[39] et al studied the occlusal contacts in the ICP under different bite force recorded by transillumination of a silicone interocclusal record. The results showed that, after a certain guidance and practice, the subjective classification of bite force was reliable, and there was no difference of occlusal contacts at the same pressure in the same individual. Botsford, KP et al[40] evaluated the precision of the virtual occlusal record by using an IOS. No statistically significant differences were observed in the proportion of location and area of the contacts between the two bite registrations. In the present study, the subjects were guided to practice tapping movement and bite in ICP under normal and most accustomed bite force. The bite force was considered to be coincident and the intraoral occlusal contacts would not change during the recording and scanning process.

However, the result showed the virtual occlusal contacts were not always coincident with the intraoral occlusal contacts even though taking tooth displacement into consideration. The occlusal contacts marked by the articulating paper are affected by the nature of the articulating paper to a certain extent. The thick paper commonly used in clinical practice is made of fibres impregnated with a dye. Dye needs to be squeezed under occlusal force to produce colouring at occlusal contact position. So the actual colouring range of articulating paper BK52 may be less than 100 μm, which results in a smaller area. On the other hand, during the process of mandible to bite in ICP, the teeth may slide slightly due to the obstruction of articulating paper and the sliding contact pattern of antagonist, and then the teeth will bite in a stable position. This process will lead to the appearance of pseudo contact markings. The virtual articulating paper method produced new occlusal surface by 'shell' function to simulate physical articulating paper thickness and found the closest point distance between new occlusal surface and opposing cast along the normal direction of the occlusal surface. All points less than 100 μm of the occlusal surfaces between casts can be calculated by this method. It may explain that the virtual occlusal contacts cannot fully predict the contacts recorded by the articulating paper intraorally and produced false-positive results.

The limitation in the current study was that standard occlusal contacts provided by 100 um articulating paper are not golden, and the articulating paper may contribute to the unsatisfactory values of sensitivity and PPV due to its physical property. It is necessary to find a more accurate and convincing way to record intraoral occlusal contacts. Another limitation was that the subjects were instructed to bite in their normal maximal ICP with most accustomed bite force, and the bite force that they exerted could not be confirmed quantitatively. Therefore, the effect of different levels of bite force on dental occlusion cannot be analysed. The next step is to use electromyography to measure muscle activity and ensure the whole process is carried out under quantitative bite force to deduce the ability to construct intercuspal occlusion of the 4 methods under different levels of bite force.

The process to segment and align single teeth are tedious, and the process to determine occlusal contacts on digital casts. To avoid the vast manual operation, artificial intelligence technology may be used to identify the gingival margins to carry out the segmented tooth registration process, select the occlusal contacts according to colour information and align casts automatically.

5 | CONCLUSION

Considering tooth displacement, the buccal bite data and occlusal contacts obtained under the ICP can be used to construct the intercuspal occlusion. The virtual dental occlusion constructed by segmented tooth registration method and occlusal contact areas (marked by 8 μm articulating paper) registration method was with better location, count and area of intraoral occlusal contacts than that of the buccal bite registration method.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

AUTHOR CONTRIBUTIONS

Hu Chen and Yuchun Sun contributed to the conception and design of the study. **Linlin Li** contributed to the acquisition and the analysis of data. **Linlin Li, Hu Chen and Yuchun Sun** contributed to the interpretation of data. **Linlin Li** contributed to the drafting of the manuscript. **All authors** involved in critically revising the manuscript and given final approval for publication.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study will be freely available to any scientist wishing to use them for non-commercial purposes by contacting the corresponding author without breaching patient confidentiality.

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