AMERICAN COLLEGE OF PROSTHODONTISTS
Your smile. Our specialty.

The Accuracy of Transferring Casts in Maximal Intercuspal Position to a Virtual Articulator

Mingzhu He, BDS,[1] Qian Ding, DDS,[1] Linlin Li, BDS,[2,3] Guangju Yang, DDS,[1] Yijiao Zhao, MSC,[2,3] Yuchun Sun, DDS,[2,3] & Lei Zhang, DDS[1]

[1]Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, China
[2]Center of Digital Dentistry, Peking University School and Hospital of Stomatology, Beijing, China
[3]National Engineering Laboratory for Digital and Material Technology of Stomatology, Research Center of Engineering and Technology for Digital Dentistry, Beijing, China

Keywords
Accuracy; occlusion; transfer plate; virtual articulator; maximal intercuspal position.

Correspondence
Lei Zhang, Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, China.
Email: drzhanglei@yeah.net

Authors Mingzhu He and Quian Ding contributed equally to this work.

Accepted June 29, 2021

doi: 10.1111/jopr.13405

Abstract

Purpose: To analyze the accuracy of transferring casts in maximal intercuspal position to a virtual articulator by using transfer plates in the laboratory scanner before and after occlusal optimization.
Material and methods: Five sets of standard dental casts were mounted on a mechanical articulator in maximal intercuspal position. The number and position of occlusal contacts were determined with 12-μm articulating foil. After a calibration process according to the manufacturer's instructions, the mountings were transferred to a virtual articulator using the transfer plates in a laboratory scanner. The occlusion of the digital casts was determined before and after the occlusal optimization process. Then, the sensitivity and positive predictive value were determined by comparing the occlusal contact points in the virtual articulator with those in the mechanical articulator. To evaluate trueness, the occlusal surface of the maxillary teeth in the mechanical articulator was recorded by polyvinyl siloxane occlusal record in maximal intercuspal position and retained on the mandibular arch. The trueness was calculated as the deviation between the occlusal surface of the maxillary teeth in the mechanical articulator and the virtual articulator. To evaluate precision, one set of the casts was scanned 10 times. And the deviation of the interarch position of the maxillary arches when superimposing the mandibular arches of every 2 different scans was calculated.
Results: The sensitivity before occlusal optimization (0.14 ± 0.15) was significantly lower than that after occlusal optimization (0.82 ± 0.10) ($p = 0.003$). However, there was no significant difference between the positive predictive value before (0.80 ± 0.45) and after (0.81 ± 0.09) occlusal optimization ($p = 0.952$). The trueness before (91.0 ± 10.7 μm) and after (75.4 ± 25.2 μm) occlusal optimization had no significant difference ($p = 0.249$). The precision before occlusal optimization (11.6 ± 3.8 μm) was significantly superior to that after occlusal optimization (75.6 ± 39.2 μm) ($p < 0.001$).
Conclusions: The accuracy of transferring casts in maximal intercuspal position to a virtual articulator using transfer plates in the laboratory scanner could be improved after occlusal optimization and can meet the clinical needs for occlusal design and analysis of prostheses.

An articulator is a commonly used auxiliary device to transfer the occlusal relationship in different fields of dentistry such as orthodontics, prosthodontics, and orthognathics.[1] Accuracy of transferring maximal intercuspal position (MIP) of dental casts was considered one of the key factors that determine the quality and occlusal fitness of a prosthesis. With the application of computer-aided design and computer-aided manufacturing (CAD/CAM) technology to dentistry, a virtual articulator system was explored and established to update the mechanical articulator with computer software.[2,3] Using the virtual articulator in dental CAD software to design clinical prostheses and conduct occlusal adjustment was reported to be more accurate and convenient than the mechanical articulator and to significantly improve the quality of prostheses.[4,5] However, any deviation that occurs in the virtual articulation process may have a significant influence on the accuracy of the occlusal transfer. Then, the occlusal accuracy of the prosthesis is likely to be impacted resulting in considerable chairside adjustments.[6]

Many researchers have focused on the accuracy of virtual articulators. Studies have rarely focused on the accuracy of transferring casts in MIP by transfer plates in the laboratory scanner. The virtual articulator in CAD software of the 3Shape D2000 laboratory scanner is equipped with a function that enabled occlusal optimization of occlusal contacts by translating and rotating maxillary casts. Occlusal optimization is executed by calculating minimal distances between grid points on opposing occlusal surfaces to generate maximal extent of occlusal contacts in MIP. After a literature search, it is found that no study yet has evaluated the influence of this occlusal optimization function on the accuracy of the virtual articulator.

This in vitro study aimed to evaluate the accuracy of transferring casts in MIP to a virtual articulator with the transfer plates in the laboratory scanner and to compare the accuracy of transferred occlusion before and after occlusal optimization. The null hypothesis was that there is no significant difference in the accuracy of transferring casts in MIP to the virtual articulator before and after occlusal optimization.

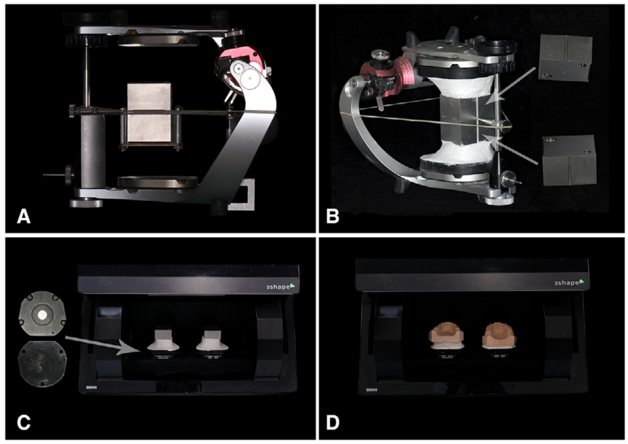

Figure 1 Calibration and scanning process. A, The customized apparatus to determine and support calibration object in the correct location of the articulator; B, the occlusal transfer calibration object mounted in mechanical articulator; C, the calibration process in scanner using the transfer plates for PROTARevo (the front and back surface); and D, scanning process for stone casts with the transfer plates.

Materials and methods

Calibration of the scanner by occlusal transfer calibration object

The occlusal transfer calibration object (3Shape A/S, Copenhagen, Denmark) was used to calibrate the position of mounted casts from the mechanical articulator to a virtual articulator. According to the manufacturer's instructions, the occlusal transfer calibration object was mounted in a mechanical articulator (PROTARevo 7; KaVo Dental GmbH, Biberach, Germany) with low-expansion gypsum (ZERO-arti; Dentona AG, Dortmund, Germany) and allowed to harden for 24 hours. The correct location was determined by a customized apparatus designed by one of the researchers (GJY) (Fig 1A). The contact surface of both parts should be located approximately in the occlusal plane of the articulator. And the incisal indicator should be in line with the vertical dot on the calibration object (Fig 1B). Then the mounted calibration object was scanned using a laboratory scanner (3shape D2000; 3shape A/S, Copenhagen, Denmark) with transfer plates for PROTARevo (3shape A/S, Copenhagen, Denmark) (Fig 1C). After calibration, the maxillary and mandibular parts of the occlusal transfer calibration object were scanned again as casts. Then, the mounted occlusal transfer calibration object was set in the calibrated virtual articulator.

The above process was repeated 5 times. All the data were imported as standard triangulation language (STL) files to the Geomagic Control software (2014; 3D Systems, Rock Hill, NC). For trueness, the root mean square (RMS) was calculated between the contact surfaces of maxillary and mandibular parts of the occlusal transfer calibration object ($n = 5$). For precision, the maxillary part of the occlusal transfer calibration object was located by aligning the mandibular part. In this way, the reference location of the maxillary part was compared with each location of each calibration ($n = 10$). The trueness of the calibration process was 18.0 ± 6.3 μm, and the precision was 19.5 ± 3.5 μm.

Virtual articulation

Five sets of standard dental casts were poured with type IV gypsum (Die stone; Heraeus Kulzer Gmbh, Hanau, Germany). The stone casts were separated 12 hours later and checked for defects and bubbles. If any defect or bubble was found, the casts would be abandoned and replaced. The casts were stored at room temperature for at least 96 hours until the plaster completely expanded. Then, the casts were manually mounted in a mechanical articulator in MIP by the same researcher, with a minimum of 5 occlusal contact points. The occlusion was checked using 12-μm articulating foil (Arti-Fol; Bausch, Nashua, NH) to ensure that each set of casts should have occlusal contact points on both the anterior teeth and posterior teeth areas, and at least 2 contact points were distributed on both sides of posterior teeth in MIP. The casts would be remounted if the occlusal contact points did not meet above criteria of occlusion. The mounted maxillary and mandibular casts were scanned simultaneously with the transfer plates (Fig 1D), and then the occlusion of the digital casts was generated in MIP in the calibrated virtual articulator, before and after conducting occlusal optimization. After every scan in this study, transfer plates were detached from the scanner and the magnetic mounting plates.

Sensitivity and positive predictive value (PV+)

Occlusal contacts were marked using 12-μm articulating foil as reference on the casts in the mechanical articulator. All contacts were displayed based on anatomic regions as described and used by Delong et al.[7] All sets of casts were scanned in the laboratory scanner and the occlusion was determined thrice in MIP in the virtual articulator with or without executing occlusal optimization, respectively, and data were exported as

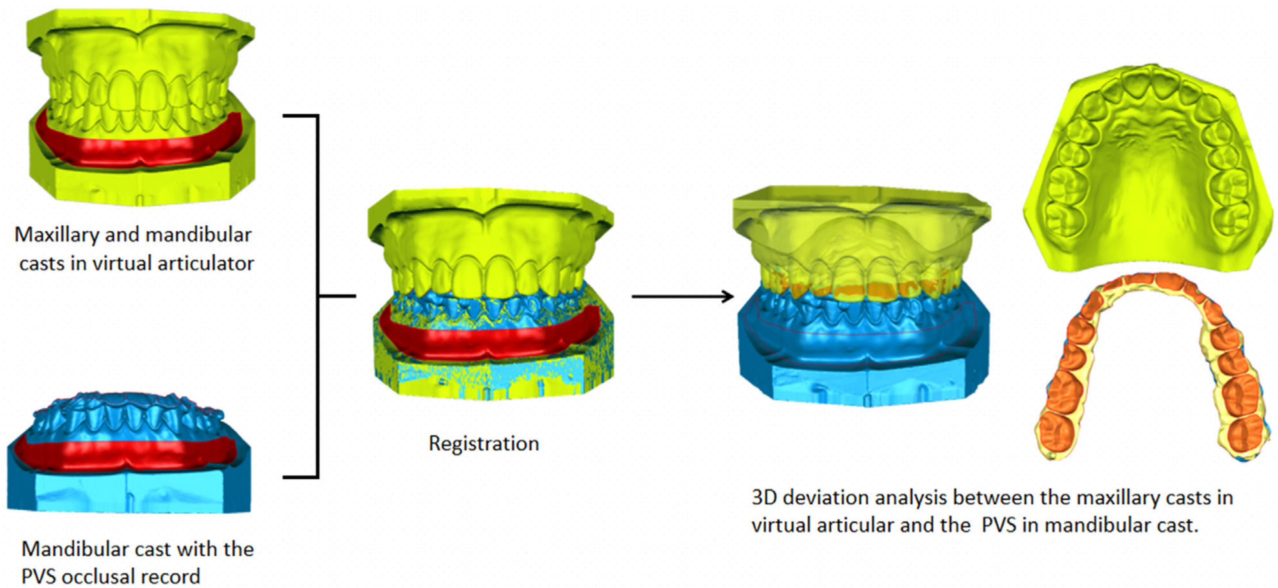

Figure 2 Workflow of trueness calculation: mandibular cast with the PVS occlusal record was registered with the mandibular cast in the virtual articulator; then, 3D deviation analysis was conducted between the maxillary casts in the virtual articulator and the PVS occlusal record on the mandibular cast.

STL files to Geomagic Control software program. By setting a threshold for the "three-dimensional (3D) compare", all occlusal areas separating or penetrating ≤20 μm were identified and defined as virtual contacts. The 2 points were considered to be separated if the centers of contact areas were more than 1 mm apart.[8] The occlusal contacts on digital cast were compared with photographs by superimposing in image processing software. The difference between the reference and virtual contacts was calculated as the sensitivity and PV+ according to Solaberrieta et al,[5] where false positive (FP), true positive (TP), true negative (TN), and false negative (FN) were obtained by counting the number of occlusal contact points in the physical and digital casts.

Sensitivity: the proportion of true occlusal contact points that are correctly identified, indicating the ability in detecting true occlusal contact.

$$\text{Sensitivity} = \frac{TP}{TP + FN}$$

Positive predictive value (PV+): the probability of contact truly existing when the diagnostic test was positive.

$$(PV+) = \frac{TP}{TP + FP}$$

Trueness

In this study, trueness was defined as the discrepancy in occlusion between the virtual articulator and the mechanical articulator. To confirm assess trueness, polyvinyl silicone (PVS) (Variotime light flow; Heraeus Kulzer Gmbh, Hanau, Germany) was injected on the entire maxillary and mandibular arches and the casts were set in MIP in mechanical articulator. A 3-kg weight was put on the articulator until PVS was completely polymerized. The articulator was carefully detached to retain the PVS occlusal record on the occlusal surface of the mandibular arch. The position of the occlusal surface of the maxillary teeth replicated by the PVS occlusal record on the mandibular arch was considered as the true position of maxillary teeth in the mechanical articulation. The mandibular cast with the PVS occlusal record was scanned alone to obtain the digital data. After scanning, the PVS occlusal record was removed from the mandibular cast. The mounted maxillary and mandibular casts were scanned with transfer plates in the laboratory scanner. The maxillary and mandibular casts in MIP in the virtual articulator were obtained before and after occlusal optimization.

The above procedures were repeated 3 times for each set of casts. All STLs were imported into the Geomagic Control software. After aligning the mandibular casts according to the common area of mandibular casts in MIP of the virtual articulator and mandibular casts with PVS occlusal records, the occlusal surface of maxillary teeth in the virtual articulator and the mechanical articulator, which was replicated by the PVS occlusal record, were compared (Fig 2). The trueness was calculated as the RMS between the occlusal surface of the maxillary teeth in the virtual articulator and the mechanical articulator (n = 5). The critical angle was set to 180° when executing "3D compare." Trueness in the anterior teeth, right posterior teeth, and left posterior teeth were calculated separately. Color-difference maps of the projections were created.

Precision

One set of casts was scanned with transfer plates 10 times in the laboratory scanner. The MIP of digital casts in the virtual articulator could be obtained before and after occlusal

Table 1 The occlusal contacts before and after occlusal optimization

Items	FP	TP	TN	FN	Sensitivity	PV+
Before occlusal optimization						
1	0	2	0	19	0.10	1.00
2	0	2	0	22	0.08	1.00
3	0	3	0	21	0.13	1.00
4	0	6	0	9	0.40	1.00
5	0	0	0	27	0	0
mean ± SD					0.14 ± 0.15	0.80 ± 0.45
After occlusal optimization						
1	2	17	0	4	0.81	0.90
2	3	19	0	5	0.79	0.86
3	6	22	0	2	0.92	0.79
4	5	10	0	5	0.67	0.67
5	4	24	0	3	0.89	0.86
mean ± SD					0.82 ± 0.10	0.81 ± 0.09

FP: false positive, TP: true positive, TN: true negative, FN: false negative.

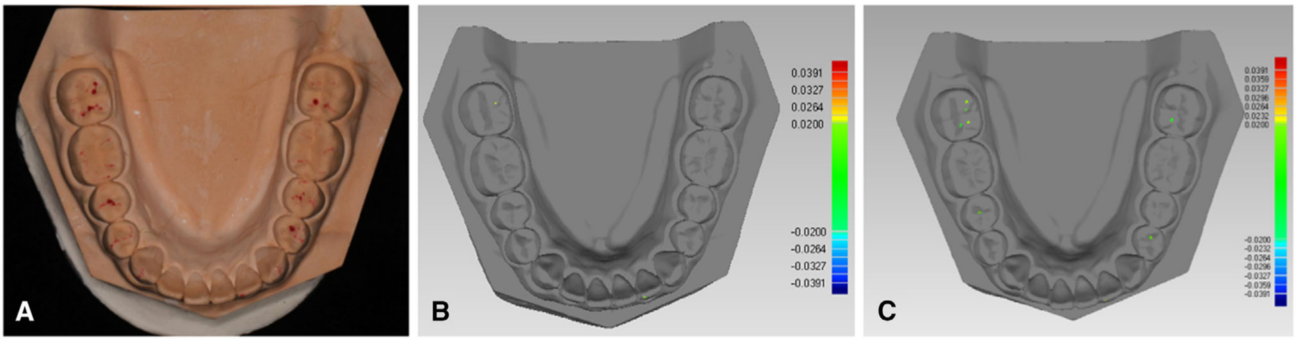

Figure 3 Occlusal contacts of casts. A, Occlusal contacts in mechanical articulator; B, occlusal contacts before occlusal optimization in virtual articulator; and C, occlusal contacts after occlusal optimization in virtual articulator. Green areas represent −20 to 20 μm of the occlusal clearance in B and C.

optimization. The maxillary and mandibular casts were merged into a single STL file according to the MIP in the virtual articulator in Geomagic Control. Then, the 20 sets of digital casts in MIP before and after occlusal optimization were obtained. After locating the mandibular cast from 2 different scans by a "best-fit algorithm" for data, the deviation of the corresponding maxillary arch could be calculated as a result of the deviation of the occlusal relationship. Then, the location of the 10 digital maxillary casts before occlusal optimization was compared with each other by superimposing and calculating the RMS as precision (n = 45). The precision after occlusal optimization was obtained with the same calculation method.

Statistical analysis

Paired *t*-test was used to verify whether there was a statistical difference in the sensitivity, PV+, trueness, and precision of the occlusion between before and after occlusal optimization. One-way ANOVA was performed to compare the trueness in 3 different regions in each group. For all the statistical tests, the level of significance was set to 0.05.

Results

Sensitivity and positive predictive value (PV+)

The sensitivity and PV+ for the 5 sets of casts are summarized in Table 1. Figure 3A shows the occlusal contacts on the physical casts. Occlusal contacts before and after occlusal optimization of digital casts are shown in Figure 3B and 3C. The sensitivity before occlusal optimization (0.14 ± 0.15) was significantly lower than that after optimization (0.82 ±0.10) ($p = 0.003$). While there was no significant difference between the PV+ before (0.80 ± 0.45) and after (0.81 ± 0.09) occlusal optimization ($p = 0.952$).

Trueness

The trueness before (91.0 ± 10.7 μm) and after (75.4 ± 25.2 μm) occlusal optimization showed no significant difference ($p = 0.249$) (Fig 4A). Trueness for the anterior teeth, right posterior teeth, and left posterior teeth before and after occlusal optimization are summarized in Table 2. Before occlusal optimization, the posterior teeth showed a significantly larger discrepancy than the anterior teeth ($p = 0.006$). After

Table 2 Mean trueness of the 3 regions before and after occlusal optimization, μm (mean ± SD) (n = 5)

Groups	Anterior teeth	Right posterior teeth	Left posterior teeth
Before occlusal optimization	67.3 ± 12.7	92.4 ± 10.8	98.0 ± 10.8
After occlusal optimization	85.5 ± 37.3	69.4 ± 18.6	73.1 ± 26.5

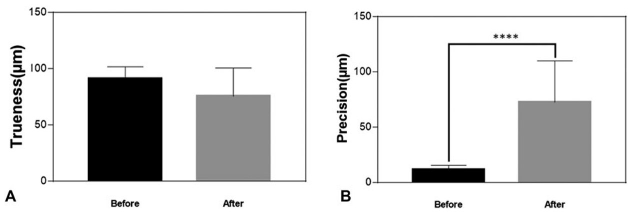

Figure 4 Trueness (n = 5) and precision (n = 45) of the occlusion in virtual articulator before and after occlusal optimization.

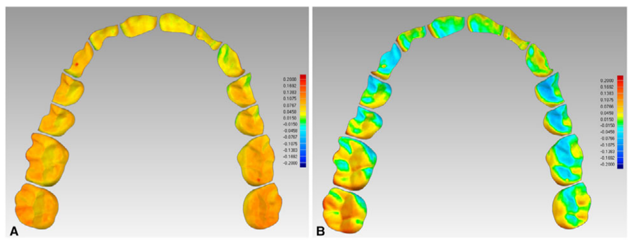

Figure 5 Deviations of occlusal surface of maxillary teeth and the PVS occlusal record retained on the mandibular arch: A, Before occlusal optimization and B, after occlusal optimization.

occlusal optimization, no statistical difference was found among the 3 regions ($p = 0.668$). The color-difference maps of the trueness before and after occlusal optimization are displayed in Figure 5, showing the most deviated regions in red/blue.

Precision

The precision before occlusal optimization (11.6 ± 3.8 μm) was significantly better than that after occlusal optimization (75.6 ± 39.2 μm) ($p < 0.001$) (Fig 4B).

Discussion

This study analyzes the accuracy of transferring physical casts from a mechanical articulator to a virtual articulator by using the transfer plates in the laboratory scanner, with and without occlusal optimization. Based on the results of the present study, with significant differences in both sensitivity and precision between before and after occlusal optimization, the null hypothesis should be rejected.

In this study, the accuracy of the calibration process itself was relatively reliable. The trueness of calibration process itself was better than that of the dental casts. Since the size of casts was larger than that of the calibration object, the RMS value of trueness deviation may be amplified in the casts under similar transfer deviation. Occlusal separation was found in the posterior teeth before occlusal optimization (Fig 5A). Especially in No. 5 cast, no occlusal contacts were found in the digital casts for all 3 scans, which resulted in a PV+ of 0. One reason could be deduced in the trueness evaluation of the calibration, where the anterior direction of the contact surface of the calibration object showed overlap, the posterior showed separation. Therefore, the occlusion of digital casts before occlusion optimization could show the same trend as that in the calibration object. Another explanation was assumed as the deviation between the contact surface of the calibration object and the occlusal plane of mounted casts may affect the occlusion in the virtual articulator. Because the contact surface of the calibration object and the occlusal plane of mounted casts were required to be consistent with the occlusal plane of the mechanical articulator according to manufacturer's instructions. The algorithm of the software and scanning accuracy might also play a role. After occlusal optimization, occlusal separation in the posterior teeth of the virtual articulator was significantly improved with more occlusal penetration areas. And the trueness after occlusal optimization was similar to that before. However, the precision before occlusal optimization was significantly better than that after. Before occlusal optimization, the repositioning deviation of KaVo adapter plates and the transfer plates caused a slight change in occlusion. This deviation may be amplified after occlusal optimization. Further, it was reported that the vertical repositioning accuracy of the KaVo adapter plates was 21.4 μm.[9] Therefore, the position change of the adapter plates with mounted dental casts would affect the trueness and precision.

Using thin articulating foil (8−12 μm) to mark occlusal contacts on dental casts was regarded as the gold standard in published literature.[5,7–8,10] To improve the consistency, Delong et al suggested that the contact tolerance variable for occlusal contact registration of digital casts should be close to the thickness of the articulating foil used on dental casts.[7] Because the measured thickness of articulating foil used in this study was 22.2 ± 1.2 μm,[11] the contact tolerance was set at 20 μm. Sensitivity >0.7 was considered to meet or exceed the clinical requirement for acceptance as a diagnostic test.[12] Delong et al compared the occlusal contacts calculated between virtual casts aligned manually, aligned with interocclusal records scanned seated on the mandibular casts or scanned independently, and directly from virtual interocclusal records. It was reported that the sensitivity ranged from 0.76 to 0.89, and PV+ ranged from 0.67 to 0.90.[7] Solaberrieta et al reported a PV+ of 0.72 for virtual occlusion aligned in 3 different reverse engineering software (Geomagic, Rapidform, and GOM Inspect).[5] In this study, the sensitivity and PV+ of occlusion in the virtual articulator after occlusal optimization were as good as the accuracy of the occlusal transfer reported in previous studies using different methods.

In previous studies, trueness was obtained by measuring interarch reference points with a coordinate measuring machine, and the deviation of distances between the reference points on the digital casts were measured and compared with the reference.[6,13–15] However, the deviation of landmarks for trueness evaluation was linear, which could not represent the deviation of occlusal surfaces. In this study, PVS occlusal records that replicated the position and anatomic morphology of the occlusal surface of the maxillary arch in MIP were considered the true occlusion in the mechanical articulator. This method for trueness evaluation has not been mentioned in previous studies. The advantage of this method is that it can quantitatively analyze the 3D deviation of the MIP in mechanical and virtual articulators.

Sophia et al[6] evaluated the static articulation accuracy of 3 laboratory scanner-CAD systems (Cremill Map400, in EosX5, Scanner S600 Arti). It was reported that the average deviations between interarch landmarks ranged from −199.0 to 40.3 μm for trueness. The errors caused by casting and mounting were reported to be 166 μm,[16–18] which were considered the error assimilated in transferring the occlusal relationship to the articulator. In previous studies in regard to the interchangeability of articulators, it was suggested that the threshold of transferring the occlusal relationship from one articulator to another should be no more than 166 μm.[19–20] Thus, the trueness of transferring the occlusal relationship from mechanical articulator to a virtual one before and after occlusal optimization were both acceptable.

Although the precision after occlusion optimization was slightly worse than those of the complete arch casts registered by 3 registration software in previous study,[5] it was within the precision range of occlusion on 3D static articulation of 3 laboratory scanners which ranged from 21.5 to 91 μm by calculating the difference of interarch distances between casts on the mechanical and virtual articulators.[6] And it was better than those of scanning quadrant arch (135 ± 77 μm) and complete arch (154 ± 59 μm) of plaster casts reported in previous study,[21] which was one of the most commonly used scanning methods in the laboratory. Therefore, the precision before and after occlusal optimization were both acceptable.

Based on the results of this study, the accuracy of using the transfer plates with a laboratory scanner to transfer casts in MIP to a virtual articulator can be considered to meet the clinical needs for digital occlusal design and fabrication of prostheses.

Some factors or procedures could cause errors in this study. First, articulating foil may produce false-positive marks.[22–23] Second, the location deviation of the calibration object in the calibration process could lead to unpredictable errors. Lastly, the error could also come from scanning dental casts and PVS occlusal records in the laboratory scanner.[24] During the calculation of trueness and precision, deviations of registering digital casts in this study were no more than 6 μm, hence, errors in registration had little effect on results.

The main advantage of the transfer plates was that they can transfer the occlusal relationship from a mechanical articulator to a virtual one, both conveniently and accurately. And virtual articulator can be used to simulate mandibular movement without wearing of the plaster cast. Interchange of articulators was reported to cause deviations in the occlusal relationship.[25] Using the transfer plates to transfer occlusal relationship can avoid transporting the articulator to the laboratory, thereby decreasing the error that may occur in mailing, transporting, and interchanging the mechanical articulator.[15]

This in vitro study has some limitations. There was no actual occlusal contact in the patient's mouth as a reference. Further research should concentrate on evaluating the accuracy of transferring MIP of actual patients to virtual articulator by the transfer plates in the laboratory scanner. In addition, the number and position of missing teeth and the distribution of occlusal contacts on the dental casts should be considered in further research.

Conclusions

The accuracy of transferring casts in MIP to a virtual articulator by the transfer plates in a laboratory scanner after occlusal optimization could be improved. The accuracy of virtual occlusion after occlusal optimization can meet the clinical needs for occlusal design and analysis of prostheses.

Funding

This work was supported by Beijing Natural Science Foundation (grant number: 7192233), Capital Health Research and Development of Special Fund (grant number: 2020-2-4104), Program for New Clinical Techniques and Therapies of Peking University School and Hospital of Stomatology (PKUSSNCT-20B02), and GuangDong Basic and Applied Basic Research Foundation (2019A1515110889).

Conflict of interest

There is no conflict of interest.

References

1. Lepidi L, Galli M, Mastrangelo F, et al. Virtual articulators and virtual mounting procedures: where do we stand? J Prosthodont 2021;30: 24-35
2. Bisler A, Bockholt U, Kordass B, et al. The virtual articulator. Int J Comput Dent 2002;5: 101-106
3. Gärtner C, Kordass B. The virtual articulator: development and evaluation. Int J Comput Dent 2003;6: 11-24
4. Koralakunte PR, Aljanakh M: The role of virtual articulator in prosthetic and restorative dentistry. J Clin Diagn Res 2014;8: 25-28
5. Solaberrieta E, Otegi JR, Goicoechea N, et al. Comparison of a conventional and virtual occlusal record. J Prosthet Dent 2015;114: 92-97
6. Yee SHX, Esguerra RJ, Chew AAQ, et al. Three-dimensional static articulation accuracy of virtual models - part I: system trueness and precision. J Prosthodont 2018;27: 129-136
7. Delong R, Ko CC, Anderson GC, et al. Comparing maximum intercuspal contacts of virtual dental patients and mounted dental casts. J Prosthet Dent 2002;88: 622-630
8. Ury E, Fornai C, Weber GW: Accuracy of transferring analog dental casts to a virtual articulator. J Prosthet Dent 2019;123: 305-313

9. Lee W, Kwon H: Vertical repositioning accuracy of magnetic mounting systems on 4 articulator models. J Prosthet Dent 2018;119: 446-449
10. Delong R, Knorr S, Anderson GC, et al. Accuracy of contacts calculated from 3D images of occlusal surfaces. J Dent 2007;35: 528-534
11. Barbosa JM, Urtula AB, Hirata R, et al. Thickness evaluation of articulating papers and foils. J Esthet Restor Dent 2018;30:70-72
12. Ogawa T, Ogimoto T, Koyano K: Validity of the examination method of occlusal contact pattern relating to mandibular position. J Dent 2000;28: 23-29
13. Yee SHX, Esguerra RJ, Chew AAQ, et al. Three-dimensional static articulation accuracy of virtual models part II: effect of model scanner-CAD systems and articulation method. J Prosthodont 2018;27:137-144
14. Iwaki Y, Wakabayashi N, Igarashi Y: Dimensional accuracy of optical bite registration in single and multiple unit restorations. Oper Dent 2013;38: 309-315
15. Hsu MR, Driscoll CF, Romberg E, et al. Accuracy of dynamic virtual articulation: trueness and precision. J Prosthodont 2019;28: 436-443
16. Breeding LC, Dixon DL, Kinderknecht KE: Accuracy of three interocclusal recording materials used to mount a working cast. J Prosthet Dent 1994;71: 265-270
17. Piehslinger E, Bauer W, Schmiedmayer HB: Computer simulation of occlusal discrepancies resulting from different mounting techniques. J Prosthet Dent 1995;74: 279-283
18. Roraff AR, Stansbury BE: Errors caused by dimensional change in mounting material. J Prosthet Dent 1972;28: 247-252
19. Chung CCJ, Chai J, Jameson LM: Interchangeability of a semiadjustable articulator. Int J Prosthodont 2001;14: 427-431
20. Pietrokovski Y, Shakartsi-Amar O, Ben-Gal G, et al. Determining the interchangeability of KaVo PROTAR semi-adjustable articulators. Quintessence Int 2018;49: 549-555
21. Iwauchi Y, Tanaka S, Kamimura-Sugimura E, et al. Clinical evaluation of the precision of interocclusal registration by using digital and conventional techniques. J Prosthet Dent 2021;25:S0022-S3913(21)00066-4.
22. Davies S, Al-Ani Z, Jeremiah H, et al. Reliability of recording static and dynamic occlusal contact marks using transparent acetate sheet. J Prosthet Dent 2005;94: 458-461
23. Velasco AB, Arenal ÁÁ, Echevarria JE, et al. Influence of articulating paper thickness on occlusal contacts registration: a preliminary report. Int J Prosthodont 2015;28: 360-362
24. Jeon JH, Kim HY, Kim JH, et al. Accuracy of 3D white light scanning of abutment teeth impressions: evaluation of trueness and precision. J Adv Prosthodont 2014;6:468-473
25. Hatzi P, Millstein P, Maya A: Determining the accuracy of articulator interchangeability. J Prosthet Dent 2001;85: 236-245