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Accuracy and Precision of Occlusal Contacts of Stereolithographic Casts Mounted by Digital Interocclusal Registrations

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Abstract

Statement of problem: Little peer-reviewed information is available regarding the accuracy and precision of the occlusal contact reproduction of digitally mounted stereolithographic casts.

Purpose: The purpose of this in vitro study was to evaluate the accuracy and precision of occlusal contacts among stereolithographic casts mounted by digital occlusal registrations.

Material and methods: Four complete anatomic dentoforms were arbitrarily mounted on a semi-adjustable articulator in maximal intercuspal position and served as the 4 different simulated patients (SP). A total of 60 digital impressions and digital interocclusal registrations were made with a digital intraoral scanner to fabricate 15 sets of mounted stereolithographic (SLA) definitive casts for each dentoform. After receiving a total of 60 SLA casts, polyvinyl siloxane (PVS) interocclusal records were made for each set. The occlusal contacts for each set of SLA casts were measured by recording the amount of light transmitted through the interocclusal records. To evaluate the accuracy between the SP and their respective SLA casts, the areas of actual contact (AC) and near contact (NC) were calculated. For precision analysis, the coefficient of variation (CoV) was used. The data was analyzed with *t* tests for accuracy and the McKay and Vangel test for precision (α=.05).

Results: The accuracy analysis showed a statistically significant difference between the SP and the SLA cast of each dentoform (P<.05). For the AC in all dentoforms, a significant increase was found in the areas of actual contact of SLA casts compared with the contacts present in the SP (P<.05). Conversely, for the NC in all dentoforms, a significant decrease was found in the occlusal contact areas of the SLA casts compared with the contacts in the SP (P<.05). The precision analysis demonstrated the different CoV values between AC (5.8 to 8.8%) and NC (21.4 to 44.6%) of digitally mounted SLA casts, indicating that the overall precision of the SLA cast was low.

Conclusions: For the accuracy evaluation, statistically significant differences were found between the occlusal contacts of all digitally mounted SLA casts groups, with an increase in AC values and a decrease in NC values. For the precision assessment, the CoV values of the AC and NC showed the digitally articulated cast's inability to reproduce the uniform occlusal contacts.

Clinical Implications: The inaccuracy of the occlusal contact reproduction of digitally produced casts increases the amount of occlusal adjustment required for the definitive restoration.

The accurate reproduction of occlusal contacts by the cast mounting process is integral to the fabrication of fixed dental prostheses. Occlusal contacts and stability are known to be one of the most important factors influencing the restoration of the dentition.[1] The clinical and laboratory processes of transferring information from the patient to the definitive dental restorations, including interocclusal registration, can be described as an accumulation of possible inaccuracies involved with each step and material used.[2, 3, 4, 5, 6, 7, 8, 9, [10, 11, 12, 13, 14, 15, 16, 17, 18 and 19] The variability inherent in the materials and methods for interocclusal registration can produce misrepresentations of the patient's occlusion.[20 and 21] The development of digital methods of recording occlusion has shown promise as a means by which dentistry can be made more comfortable, faster, and possibly of higher quality.[22, 23 and 24]

Making a digital impression is accomplished with the aid of an intraoral scanning (IOS) instrument. The scanned data is transmitted to a manufacturing center for processing of the images. The physical dental casts are then fabricated with either a subtractive computer-aided design and computer-aided manufacture (CAD-CAM) milling process[17] or an additive resin printing process known as stereolithography (SLA).[19] To mount the physical dental casts made by CAD-CAM technology, the facial (buccal) surfaces of the maxillary and mandibular teeth are scanned in maximum intercuspation (MIP); This technique is used instead of using a physical occlusal registration material, thus the CAD-CAM-generated dental casts can be mounted by using a best-fit alignment algorithm without any physical interocclusal record.[25]

Other studies have focused on comparing conventional and virtual occlusal records.[1, 25, 26 and 27] Solaberrieta et al[25] analyzed the accuracy of contacts between sets of digitized casts with 3 types of software, showing that virtual occlusion is more accurate than physical methods; the mean (standard deviation) accuracy of the virtual casts was 69 (11) μm. Maruyama et al[26] also showed virtual articulation methods created more exact contact points during excursive movements of articulated digital casts. DeLong et al[27] compared the methods of identifying occlusal contacts, such as transillumination, virtual casts, virtual MIP records, and shimstock (10 μm). They showed that when the transillumination method was used as the standard of measure, the accuracy of the virtual cast and virtual MIP records methods was much higher than when shimstock was the standard.

Few studies, however, have investigated the accuracy and precision of the digital mounting of CAD-CAM-generated dental casts. The purpose of this study was, therefore, to evaluate the occlusal contact accuracy and precision of stereolithographic (SLA) casts mounted by digital interocclusal registration. Accuracy refers to how closely the data are to a simulated patient (SP), whereas precision looks at the occlusal contact consistency of the casts to each other. In order to test accuracy, the values of occlusal contacts present in each SP were compared with the average values of occlusal contacts of their associated specimens. This test demonstrates the accuracy of SLA casts mounted with a digital interocclusal registration. The null hypothesis of the accuracy test was that no significant difference would be found between the occlusal contacts from digitally mounted casts and the SP. To test precision, the occlusal contacts of all specimens in each group were compared. This precision test demonstrates how closely the digital mountings can be reproduced. The null hypothesis regarding precision was that no significant difference would be found among all specimens of each group.

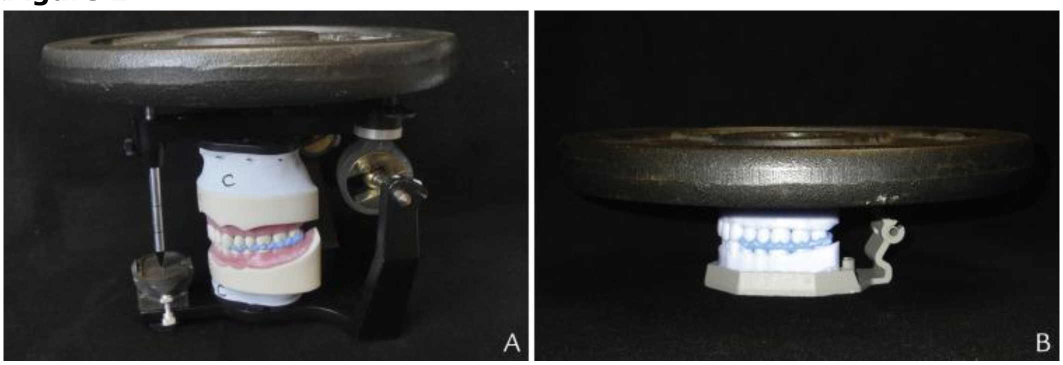
Material and Methods

Four complete anatomic dentoforms (M-1560; Columbia Dentoform Corp) were arbitrarily mounted as the 4 different simulated patients (spA, spB, spC, and spD) on a semi-adjustable articulator (Hanau wide-vue articulator; Whip Mix Corp) with centric locks engaged in MIP and with Type III dental stone (Mounting stone; Whip Mix Corp). In this case, any inaccuracies associated with the original articulation were ignored because the comparison was made only between the SP and the casts of each group. A total of 60 digital impressions (15 per each SP) were made with a digital intraoral scanner (Lava Chairside Oral Scanner; 3M ESPE). Each digital impression consisted of all supragingival surfaces of all teeth, replicating the entire dentition of the simulated patient. Each impression was visualized and inspected to prevent any scanning errors. The digital intraocclusal registrations were made for each digital impression according to the manufacturer guidelines; the occlusion was captured by digitally recording the buccal surfaces of the teeth while the SP was closed in MIP. The digital impression files were sent electronically to the 3M Lava center to fabricate 15 sets of mounted SLA definitive casts for each group.

After receiving a total of 60 SLA casts for 4 sp groups (spA, spB, spC, and spD), polyvinyl siloxane (PVS) interocclusal records (Jet-

Blue; Coltène/Whaledent) were made twice over the entire occlusal surfaces of the posterior teeth from first premolar to third molar bilaterally. A total of 240 PVS records (2 times × 2 sides × 60 casts) were made with a 49-N load placed on the center of the articulated casts to ensure full contact between opposing teeth was present, allowing the PVS to polymerize under the same occlusal force for each set of casts (Fig. 1).[28] The excess registration material of the right and left records were trimmed with a laboratory scalpel to attain uniformly flat surfaces on the borders to aid in level placement into a scanner.

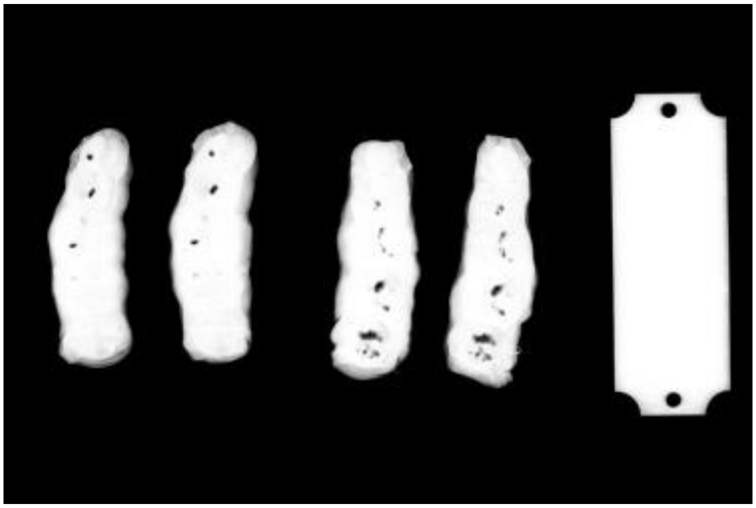
Figure 1.



A, Occlusal records and simulated patient model mounted on articulator with 49-N load. B, Occlusal records and digitally mounted stereolithographic cast with 49 N load.

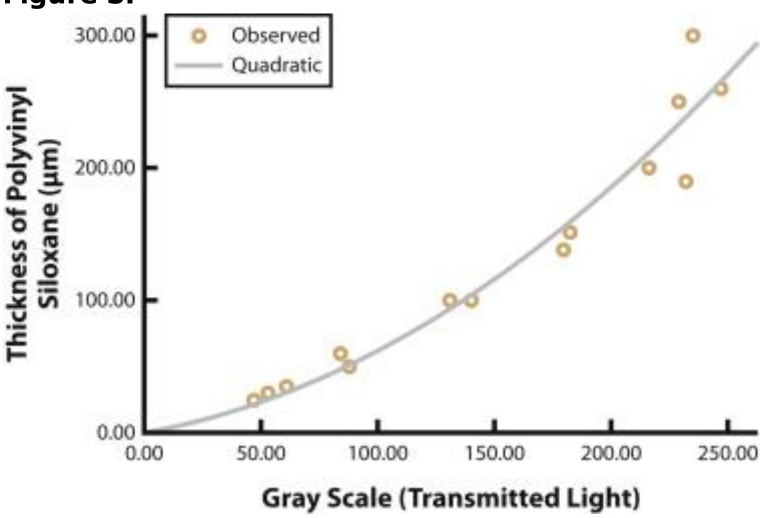
A double-sided flatbed scanner (Expression 1680; Epson America) was used to produce grayscale scans of each PVS interocclusal record in a negative mode with 600 dots per inch (dpi) (Fig. 2). The scanning data were analyzed with computer software (ImageTool v3.0; University of Texas Health Sciences Center at San Antonio), providing the optical density of the transmitted light through the occlusal records.[2, 18 and 29] A calibration step wedge was fabricated with PVS interocclusal record material before the occlusal registrations was scanned. A wedge with 13 known thicknesses was scanned to formulate a regression equation relating transmitted light to PVS thickness based on the pixel grayscale (GS) values. The thickness was then calculated by the following derived equation: $Thickness=0.0042(GS)^2-0.0293(GS)+22.373$ (Adj R-square=0.933). When the intercept term was forced to be 0, the regression equation yielded the following equation: $Thickness=0.0031(GS)^2+0.3152(GS)$ (Adj R-square=0.979) (Fig. 3).

Figure 2.



Grayscale scans of 4 polyvinyl siloxane interocclusal records by double-sided flatbed scanner.

Figure 3.



Calibration step wedge data for relationship between gray scale (transmitted light) and thickness of polyvinyl siloxane registration.

To compare the occlusal contact reproduction among the SP (control) and specimen (SLA cast group), the areas of actual contact (AC) and near contact (NC) were calculated. An AC was considered to be 0 µm to 50 µm in thickness, while a NC was considered to be 51 µm to 300 µm in thickness.[2, 18 and 29] The areas of AC and NC were recorded in square millimeters. All data analyses were performed with software (SPSS v22; IBM Corp). In order to compare the SLA cast averages to the associated sp, Student *t* tests were used (α=.05). The

Bonferroni correction was applied for multiple hypotheses. The coefficient of variation (CoV) was adopted to determine the precision of the measurements for each group. This measure expressed the standard deviation as a fraction of the sample mean where a low CoV indicates high precision. The McKay and Vangel test was used to evaluate whether CoV is equal to 10% (α=.05). [30]

Results

Figure 1 shows the relationship graph of transmitted light to PVS thickness. For purposes of calibration, the material thickness from 25 μm to 260 μm and gray values from 47 to 246 were calculated. The light transmitted for the AC had GS values between 0 and 80. The light transmitted for the NC showed the GS values between 81 and 246.

Table 1 summarizes the accuracy analysis with a quantitative comparison of the mean ± SD (mm^2) of the AC and NC between the sp and SLA casts of the 4 dentoforms (A, B, C, and D). Overall, a statistically significant difference was found between the SP and SLA casts of each dentoform. For the AC of all dentoforms, a significant increase was found in the occlusal actual contact areas of SLA casts when compared with the contacts of the sp. In contrast, in evaluating the NC of all dentoforms, a significant decrease of the occlusal near contact areas present in the SLA casts was demonstrated when compared with the contacts in the sp.

Table 1. Quantitative analysis (familywise α=.05) for comparison of occlusal contacts between SPs and each dentoform according to Student *t* test

	Dentoform A Mean ±SD (mm^2)		**Dentoform B Mean ±SD (mm^2)**		**Dentoform C Mean ±SD (mm^2)**		**Dentoform D Mean ±SD (mm^2)**	
	spA	**SLA cast A**	**spB**	**SLA cast B**	**spC**	**SLA cast C**	**spD**	**SLA cast D**
AC	6.84 ±0.21	21.38 ±1.57	6.11 ±0.21	20.94 ±1.83	15.02 ±0.29	21.50 ±1.63	2.95 ±1.78	22.42 ±1.30
P	<.001		<.001		.002		<.001	
NC	62.69 ±1.68	52.74 ±16.76	75.80 ±6.10	46.50 ±14.38	112.02 ±9.98	57.07 ±25.45	63.43 ±5.44	55.12 ±11.80
P	.038		.002		<.001		.016	

AC, actual contact; NC, near contact; SLA, stereolithographic; sp, simulated patient (A, B, C, D).

Table 2 shows the precision analysis with the CoV values and 95% confidence interval (CI) of all 4 dentoforms for the AC and NC, which illustrates the occlusal contact uniformity between SLA casts from each dentoform. The precision of the occlusal contact reproduction in digitally mounted SLA casts demonstrated values between AC (95% CI; 5.8-8.8%) and NC (95% CI: 21.4-44.6%).

Table 2. AC and NC for each dentoform with McKay and Vangel statistical analyses at α=.05

	Dentoform A-SLA Casts		**Dentoform B-SLA Casts**		**Dentoform C-SLA Casts**		**Dentoform D-SLA Casts**	
	AC	**NC**	**AC**	**NC**	**AC**	**NC**	**AC**	**NC**
CoV (%)	7.4	31.8	8.8	30.9	7.6	44.6	5.8	21.4
95% CI	5.4-11.6	22.8-54.6	6.2-14.6	21.8-56.1	5.3-13.4	30.0-100.0	4.2-9.2	15.5-35.0
P	.18	1.00	.62	1.00	.33	1.00	.02	1.00

CI, confidence interval; CoV, coefficient of variation. Other abbreviations as shown in Table 1.

Discussion

The study quantitatively evaluated the occlusal contacts of the SLA casts mounted by digital interocclusal registration in terms of accuracy and precision. The overall statistical analyses for the accuracy and precision evaluation rejected the null hypothesis of accuracy (Tables 1, 2). This study indicated that the occlusal contacts of digitally mounted SLA casts differed quantitatively from the contacts present in the SPs, both in terms of the AC and NC areas.

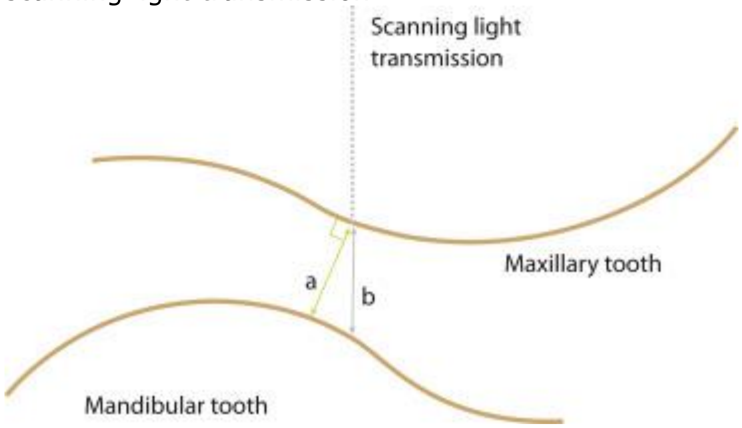
Regarding the accuracy evaluation, the values of AC of digitally mounted SLA casts demonstrated an increase in occlusal contact areas, while the values of NC present in digitally mounted SLA casts showed a decrease of occlusal contact areas. This means that the dimension and surface of the SLA casts at the AC and NC areas were altered in different ways. First, the accuracy of the occlusal contacts can be influenced by the dimension of CAD-CAM fabricated casts.[19, 25 and 31] Cho et al[31] showed digital casts produced less accuracy than the conventional casts in terms of the entire cast areas, with the mean discrepancy of 27 ±7 μm for digital casts and 11 ±3 μm for the conventional casts. In addition, Patzelt et al[19] demonstrated the different dimensional accuracy of definitive casts made by the different intraoral scanners (IOS) systems. Milled casts (iTero; Align Technology Inc, 98.23 µm) were found to be less accurate than SLA casts (Lava Chairside Oral Scanner; 3M ESPE=67.50 µm; and CEREC Bluecam; Sirona=75.80 µm). The respective patterns of the dimensional change for these 2 types of CAD-CAM-generated dental casts were also brought to light. The SLA-based casts were affected by centripetal shrinkage with horizontal contraction at the posterior area, whereas milled casts showed a centripetal expansion with horizontal expansion located in the posterior region. This discovery emphasized the potential risk of distortion in CAD-CAM-generated casts, especially in the posterior region.

Additionally, studies demonstrated that complete-arch scanning was less accurate than small area scanning.[32 and 33] Because the mounting of digital casts on the basis of CAD-CAM technology consists of many steps, including data acquisition, data processing, manufacturing, and articulating, the inherent inaccuracies during the cast fabrication process might result in erroneous cast mounting and occlusal contact reproduction. Besides gross discrepancies, the surface quality of the CAD-CAM casts can also affect the accuracy values. SLA casts are made by the polymerization of a liquid photopolymer by laser light, resulting in a surface with slight rippling where the sequential layers are stacked on top of each other.[19] This layer-by-layer buildup technique creates a stair-step effect of the object's surface.[34] The resulting stair-step effect can cause a rough texture with dimensional errors.[34] A critical factor in the surface structure of SLA casts is the thickness of each layer, with a greater number of thinner layers leading to a more accurate product. To summarize, the degree of surface smoothness can contribute to the level of accuracy seen in the AC and NC areas evaluated in this present study; because the surface is not perfectly smooth, the AC and NC of digitally mounted SLA casts can be affected differently.

Other factors can influence the ability to reproduce AC and NC, for example, virtual alignment technologies, the algorithm used, and the measurement technique. DeLong et al[1] investigated 4 different methods of virtual alignment technologies, manual alignment, alignment with a seated scanned interocclusal record, alignment using independently scanned interocclusal records, and directly from virtual interocclusal records. That research indicated that virtual methods are a valid means of reproducing contact areas present in the occlusion of stone casts marked with film. None of those methods, however, were in perfect agreement with the standard contacts because of the data filtering and averaging that occurs during the production of a merged data file. In addition, the effect of the dimension and location of virtual occlusal records should be taken into consideration when judging accuracy.[33] Solaberrieta et al[33] found that the 12×15-mm dimension was the minimum optimum dimension for a virtual occlusal record. After data are collected with IOS technology, the process of digital mounting involves a reverse engineering software.[25, 35 and 36] Some software can lead to statistically significant variations in the contralateral occlusion because of the differences in algorithms of the software used.[35]

Algorithms are essentially different methods of creating the cast.[25] By recording a more exact maxillary arch position in relation to the hinge axis for digital casts, the algorithm has been shown to be accurate enough for dental procedures.[36] Last, another influencing factor is the measuring method used. Even though the virtual occlusal record has no physical material, the transillumination method uses the PVS material to calculate the transmitted light with the aid of a scanner. Therefore, the angle of scanning light may affect the resulting light transmittance more. Because the occlusal surfaces of opposing teeth are curved with cusps and fossae, the distance (thickness) of the PVS registration would be different depending on the location and angle of measuring line (Fig. 4). In addition, the various angles of the scanning light could cause variations in AC or NC depending on the vector angle of light passing through the PVS materials for each specimen. This means that the trimming of the edges of the PVS interocclusal records by hand may have resulted in inconsistent shape and extension, which would result in slight different distances and angles of the scanning light transmittance (Fig. 4). Because of this drawback associated with the transillumination method, alternative implementations, such as T-scan (Tekscan, Inc) and articulating papers, should be considered for further studies.

Figure 4. Schematic diagram shows potential error of thickness measurement by transmission method because of various location and angle of measured thickness: a, closest distance (thickness of polyvinyl siloxane material) between 2 surfaces; b, distance measured by given angle of scanning light transmission.



Precision, expressed as CoV percentage, was used to determine the reproducibility of the occlusal contacts among the 15 SLA casts per group. A large CoV value indicates low precision. CoV values were used instead of standard deviation statistics because of the inability to make comparisons among different studies when standard deviation was used, as standard deviation is specific only to a particular study. CoV values, however, serve to standardize the data among various studies. The value of 10% was used because a value of less than 10% indicates precise data.[37] The CoV values of the AC of all dentoforms ranged from 5.8% to 8.8%. Even though the CoV values of the AC were less than 10%, the *P* values (>.05) of all CoV of the AC for all the dentoforms except dentoform D did not indicate high precision. In contrast, the CoV values of the NC of all dentoforms ranged from 21.4% to 44.6%. Therefore, in terms of overall precision regarding AC and NC, the precision of the SLA cast showed low precision (Table 2). This precision of the occlusal contacts presented in this study can be associated with the precision of the dimension of CAD-CAM-generated dental cast. [19 and 31] Patzelt et al[19] demonstrated the precision values of the CAD-CAM-generated dental cast by Lava Chairside Oral Scanner, CEREC Bluecam, and iTero were 13.77 µm (95% CI: 2.76-24.79), 21.62 µm (95% CI: 10.60-32.63), and 48.83 µm (95% CI: 37.82-59.85). Cho et al[31] showed the precision values of the CAD-CAM-generated dental cast by Lava Chairside Oral Scanner was 91µm (95%

CI: 79-104), compared with the precision value of the conventional stone casts (54 µm; 95% CI: 47-62). Therefore, the precision of the occlusal contacts of digitally mounted casts can be influenced by the precision of CAD-CAM-generated dental casts.

This research has several limitations with respect to the methods and materials used. The present study only analyzed the quantitative values of the occlusal contacts, not the qualitative values. In addition, the simulated loading force used during the PVS interocclusal record fabrication should be considered. Ghazal et al[21] showed a compressive force of 10 N can be used to stabilize a set of casts during mounting procedures for PVS materials. However, no study investigating the effect of more than 10 N of loading for PVS materials is available. That being said, maximum human occlusal forces for adult women and men are approximately 200 and 300 N.[38] The assumption made for the present study was that dental patients would not close into the occlusal record with maximum occlusal force. To stay under the maximum occlusal force but also allow full closure into the PVS record material, a 49 N load was selected for this study. Another limitation of the present study was the lack of a comparison with conventional stone casts articulated by conventional occlusal records. Because the dimensional accuracy (11 ±3 µm) of stone casts has been found to be higher than the dimensional accuracy (27 ±7 µm) of CAD-CAM-generated dental casts,[19 and 31] the effect of the dimensional distortion present in stone casts on occlusal contact reproduction would be minimal. In terms of materials, each time an occlusal registration was made, a slightly different amount of material was placed on the occlusal table of the SLA cast. As such, a varying amount of material would be displaced to the lingual and buccal areas of the arch. Lastly, the results may not be applicable to other CAD-CAM technologies. Because the results were based on only 1 intraoral scanner and 1 measuring method, further studies will be needed to investigate the accuracy and precision of other comparative technologies and methods.

Conclusions

For accuracy evaluation, statistically significant differences were found between the occlusal contacts of all digitally mounted SLA cast groups, with an increase in AC values and a decrease in NC values. For precise assessment, CoV values of the AC and NC showed the inability of the digitally articulated cast to reproduce uniform occlusal contacts.

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