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RESEARCH AND EDUCATION

Comparison of different intraoral scanning techniques on the completely edentulous maxilla: An in vitro 3-dimensional comparative analysis

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ABSTRACT

Statement of problem. Information about the accuracy of intraoral scanners for the edentulous maxilla is lacking.

Purpose. The purpose of this in vitro study was to compare the accuracy of 3 different intraoral scanner techniques on a completely edentulous maxilla typodont.

Material and methods. Two completely edentulous maxillary typodonts with (wrinkled typodont) and without (smooth typodont) palatal rugae were used as reference and were scanned by using an industrial metrological machine to obtain 2 digital reference scans in standard tessellation language (STL) format (dWT and dST). Three different scanning techniques were investigated: in the buccopalatal technique, the buccal vestibule was scanned with a longitudinal movement ending on the palatal vault with a posteroanterior direction; the S-shaped technique was based on an alternate palatobuccal and buccopalatal scan along the ridge; in the palatobuccal technique, the palate was scanned with a circular movement and then with a longitudinal one along the buccal vestibule. Consecutively, 6 types of scans were obtained (n=10), namely wrinkled typodont/buccopalatal technique, wrinkled typodont/S-shaped technique, wrinkled typodont/palatobuccal technique (wrinkled typodont), smooth typodont/buccopalatal technique, smooth typodont/S-shaped technique, and smooth typodont/palatobuccal technique (smooth typodont). Scans in STL format were imported into a dedicated software program, and trueness and precision were evaluated in µm. In addition to descriptive statistics (95% confidence interval), a 2-factor ANOVA on the data ranks, the Kruskal-Wallis, and the Dunn tests were performed to analyze differences among groups (α=.05).

Results. Mean values for trueness (95% confidence interval) were wrinkled typodont/buccopalatal technique=48.7 (37.8-59.5); wrinkled typodont/S-shaped technique=65.9 (54.9-77.4); wrinkled typodont/palatobuccal technique=109.7 (96.1-123.4); smooth typodont/buccopalatal technique=48.1 (42.4-53.7); smooth typodont/S-shaped technique=56.4 (43.9-68.9); smooth typodont/palatobuccal technique=61.1 (53.3-69), with statistically significant differences for wrinkled typodont/buccopalatal technique versus wrinkled typodont/palatobuccal technique (P<.001), buccopalatal technique versus palatobuccal technique (P<.001), and wrinkled typodont versus smooth typodont (P=.002). Mean values for precision (95% confidence interval) were wrinkled typodont/buccopalatal technique=46.7 (29.7-63.7); wrinkled typodont/S-shaped technique=53.6 (37.6-69.7); wrinkled typodont/palatobuccal technique=90 (59.1-120.9); smooth typodont/buccopalatal technique=46 (39.7-52.3); smooth typodont/S-shaped technique=76 (55.5-96.6); smooth typodont/palatobuccal technique=52.9 (41.9-63.8); with statistically significant differences for buccopalatal technique versus palatobuccal technique (P=.032) and wrinkled typodont/buccopalatal technique versus wrinkled typodont/palatobuccal technique (P=.012).

Conclusions. Smooth typodont scans showed better trueness than wrinkled typodont scans. Buccopalatal technique showed better mean values for trueness and precision than palatobuccal technique only in the wrinkled typodont scenario, while the other scanning approaches did not show significant differences in either tested configuration. (J Prosthet Dent 2020;124:762.e1-e8)

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Clinical Implications

The scan strategy used influences the trueness and precision of completely edentulous maxilla scans with the TRIOS 3 intraoral scanner.

Digital technology and intraoral scanners (IOSs) have become popular in dental practice and have advantages over conventional impression techniques, including reduced laboratory and chair time[1-14] and implementation of a completely digital production workflow.[1,14] However, disadvantages include the learning curve,[15] the limited accuracy for completely edentulous arches[16] and complete-arch implant-supported prostheses,[17] and the cost of the IOS.[14] Nevertheless, cost savings can be expected on materials, shipping, and dental laboratory bills, and the procedure should be more efficient with fewer remakes.[2,18]

IOS systems have been reported to have variable levels of overall accuracy in digital datasets,[19,20] with in vitro and in vivo investigations reporting differences from confounders such as the IOS system, scanning technique, light source, imaging type, necessity of coating or powdering, tooth morphology, tissue mobility, and span length.[14,16,21,22] Significant differences have been reported among dentate, partially, or completely edentulous scans.[14,23] The accuracy of optical scans has been reported to be clinically satisfactory for single crowns and in fixed dental prostheses up to 5 units[8,24]; however, the accuracy of digitizing complete dental arches depends on the technology of the IOS, and clinically acceptable results have been reported to be reliable only for scans of less than half the arch.[25,26]

The scanning of partially and completely edentulous arches still represents a clinical challenge, particularly because of the lack of clear landmarks in edentulous areas with the absence of anatomic reference points,[14,16,22,25] the anatomic limitations to the IOS access in the posterior regions,[14] the impossibility of recording the tissues under selective pressure,[27,28] and the inability to record the soft tissue dynamics (activated borders of denture bearing areas).[14,28] The trueness for complete dentition scanning has been reported to be between approximately 17 μm and 378 μm and the precision between 55 μm and 116 μm.[25] For edentulous arches, the trueness ranged between 44.1 μm and 591 μm, while the precision was up to 698 μm.[22] In general, all scanners can be considered accurate for scanning a complete dentition, particularly for single prepared teeth, while for edentulous arches, scanner accuracy remains questionable because of high variability.[22,25]

Traceable structures and rough surfaces provide much optical information to improve the stitching process of images and videos with dedicated software programs, thereby enhancing the scanning accuracy.[16,29] Conversely, the scanning of flat or smooth surfaces, as for anterior teeth or level edentulous ridges, can lead to software errors in the digitization.[16,21,29] Moreover, the palatal vault may negatively affect the accuracy of scans,[16,29] and the placement of artificial landmarks in edentulous areas could enhance scan accuracy.[22] Whether the surface topography of palatal rugae, representing potential traceable structures on the completely edentulous maxilla, affects the accuracy of scanning is unclear.

The fully digital workflow has become popular in removable prosthodontics because of the improvement in optical scanners and the development of dedicated functions in the related software programs.[30-34] Different scanning techniques have been compared for dentate arches[35-39] and for completely edentulous arches.[30,31] These have been described in clinical reports[32-34] and in experimental studies,[16,40,41] but comparative data are lacking.

The purpose of the present in vitro study was to compare the accuracy of 3 different scanning techniques with one IOS (TRIOS 3 Pod; 3Shape A/S) on 2 similar reference typodonts representing the completely edentulous maxilla, characterized by the presence or absence of palatal rugae. The null hypothesis was that no significant differences would be found among the different scanning strategies performed with IOS on 2 reference typodonts.

MATERIAL AND METHODS

Two reference typodonts (Fig. 1) were manufactured by pouring polyurethane resin (PRIMA-DIE; Gerhò S.P.A.) into a mold of a standard edentulous maxilla with well-defined palatal rugae obtained from a patient's cast previously used for a clinical procedure and duplicated with a silicone material (Elite Double 8; Zhermack SpA). Subsequently, 1 of these typodonts was modified by removing the palatal rugae and smoothing the surface of the edentulous ridge with rotary instruments (AcryPoint; SHOFU Dental Corp) and polishing paste (Universal Polishing Paste; Ivoclar Vivadent AG). In this way, compared with the "wrinkled typodont" (WT), the "smooth typodont" (ST) exhibited less defined anatomic landmarks because of the absence of palatal rugae and the edentulous ridges were smooth. Both typodonts had a matt finish, and because polyurethane acts as an optimal light diffuser[42] for IOS procedures,[19] no surface treatments that might have influenced the scanning were made. WT and ST were scanned by using a metrological scanning machine (Atos Core 80; GOM) based on a structured white-light technology with the following settings: working distance=170 mm, point spacing=0.03 mm,

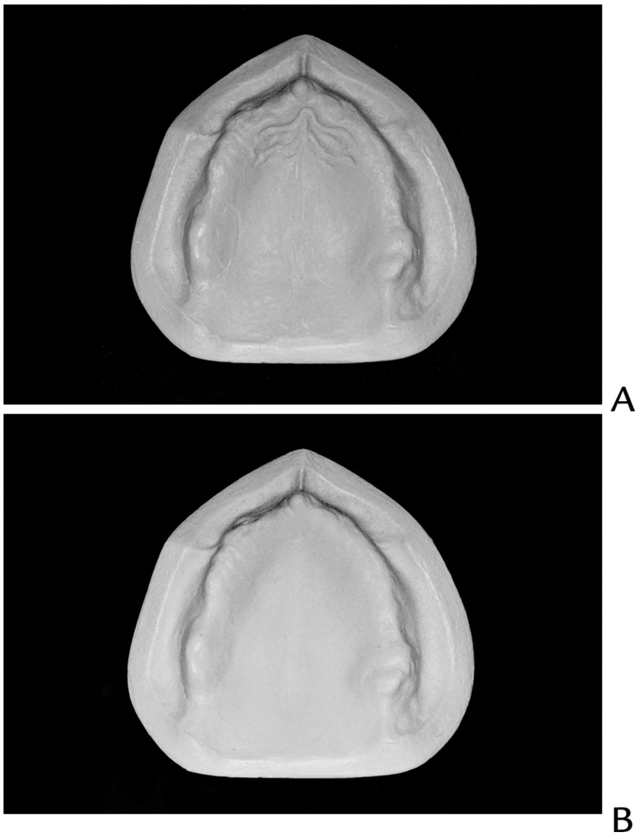

Figure 1. Reference typodonts. A, Wrinkled typodont with palatal rugae. B, Smooth typodont without rugae.

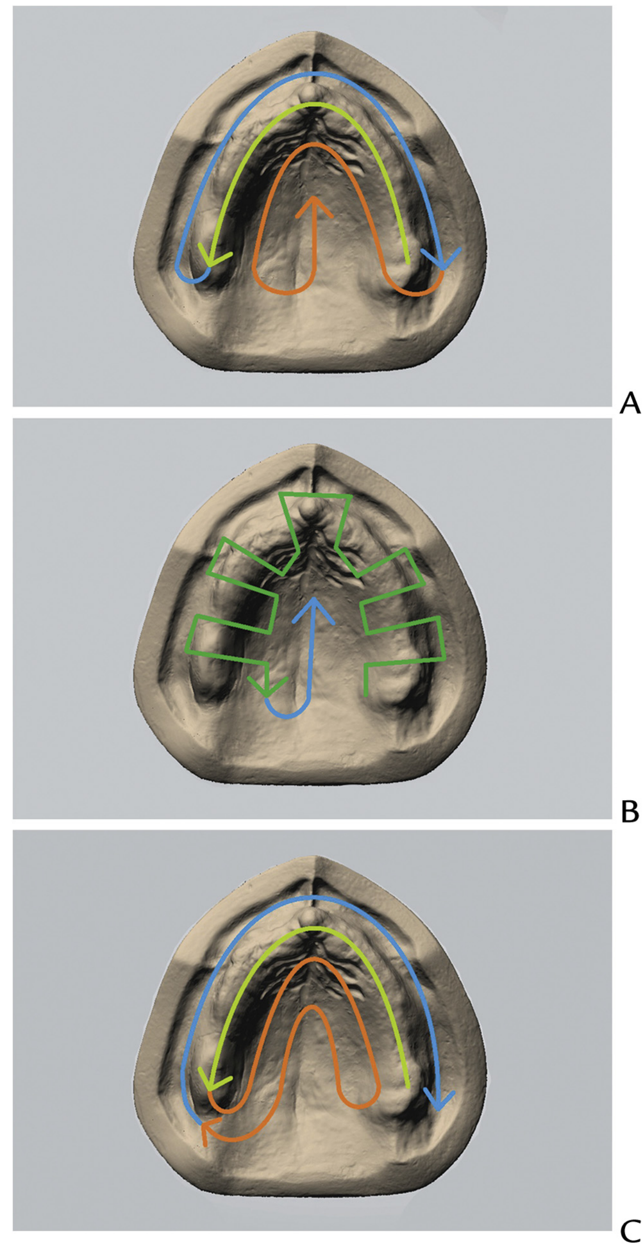

Figure 2. Scanning techniques. A, Buccopalatal. B, S-shaped. C, Palatobuccal.

and measure accuracy=±0.0025 mm. Subsequently, 2 digital reference scans were made in standard tessellation language (STL) format: “dWT” for WT and “dST” for ST.

The 2 reference typodonts were then scanned by using an IOS system (TRIOS 3 Pod; 3Shape A/S) as per 3 scanning techniques to obtain 10 experimental scans per group. The number of scans per group was determined based on convenience criteria validated by previous investigations.[27,36,43-45] The 3 scanning techniques were the following: in the buccopalatal technique (BP), the ridge top side of the edentulous arch was first scanned starting from the left maxillary tuberosity, proceeding longitudinally along the ridge, ending at the right tuberosity, and then continuing on the buccal side and finally on the palatal vault; the latter was first scanned with a counterclockwise movement along the palatal vault and finally with a longitudinal movement in the posteroanterior direction to close the gap along the midline of the palate (Fig. 2A); in the S-shaped technique (SS), the scanning started from the palatal side of the left maxillary tuberosity by moving the scanner tip with alternate palatobuccal and buccopalatal S-shaped movements along the ridge, from one side to the other; finally, the area along the palatal midline was recorded in the posterior-anterior direction (Fig. 2B); in the palatobuccal technique (PB), the scanning proceeded longitudinally along the ridge top side of the complete arch, starting from the left maxillary tuberosity and ending at the right one, and then continuing on the palatal side and finally on the buccal side. The palatal side was scanned with a circular movement in a clockwise direction along the palatal vault up to the left maxillary tuberosity and finally with a counterclockwise movement up to the contralateral tuberosity (Fig. 2C).

One prosthodontist (G.R.) performed all the scans during the same day and in the same room under similar light and environmental conditions: temperature of

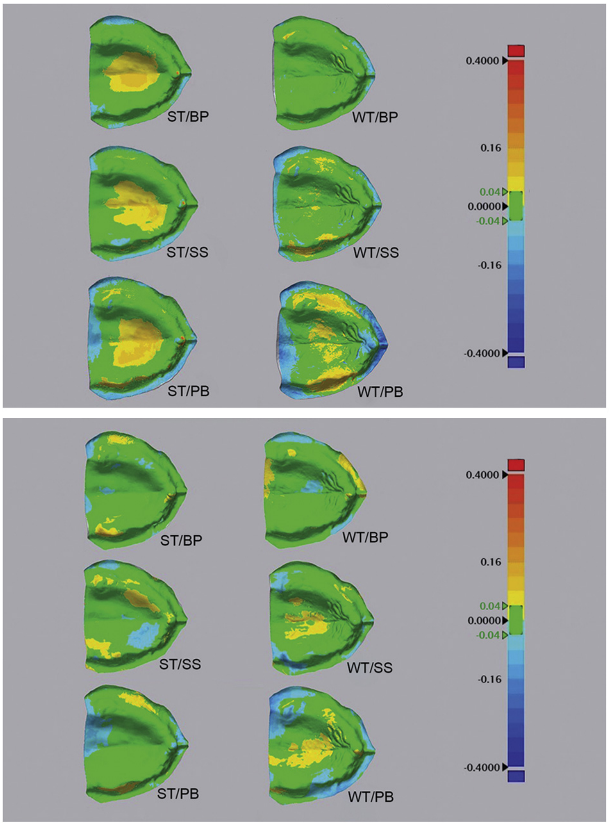

Figure 3. Best superimposition for each group of scans: *Green areas* indicate minimum displacements of ±0.04 mm of digital cast compared with reference data. *Red areas* indicate outward displacement of +0.4 mm and *blue areas* inward displacements of -0.4 mm. A, Evaluation of trueness. B, Evaluation of precision. BP, buccopalatal technique; PB, palatobuccal technique; SS, S-shaped technique; ST, smooth typodont; WT, wrinkled typodont.

22 °C, air pressure of 760 ±5 mmHg, and 45% relative humidity. The number of images per scan varied between 408 and 1126, and the scanning time was between 1 and 2 minutes. To reduce the effect of operator fatigue and to prevent related bias, the scanning sequence was randomized by using a random sequence generator (Random Number Generator Pro v.1.72; Segobit Software), and an interval of 10 minutes was allowed so that the operator could rest and the device could properly cool.[1,46] All STL files acquired with the IOS were imported into a dedicated software program (MeshLab v2016.12; ISTI-CNR) by using dWT and dST as guides to cut the surplus surfaces of each experimental scan.

Both the reference and experimental scans were imported into an inspection software program (Geomagic Control X; 3D SYSTEMS) (Fig. 3), and the accuracy of each one was evaluated by calculating trueness and precision in µm.[47] The scans made on WT were superimposed on dWT, while those made on ST were

Table 1. Results (µm) for trueness: mean, lower-upper bound (95% confidence intervals), standard error, median, and interquartile range

Groups	Mean	Lower-Upper Bound	Standard Error	Median	Interquartile Range
WT/BP	48.7	37.8-59.5	4.7	43.4	14.8
WT/SS	65.9	54.9-77.4	5.1	64.6	16.8
WT/PB	109.7	96.1-123.4	6	106.1	33.4
ST/BP	48.1	42.4-53.7	2.4	48.9	13.7
ST/SS	56.4	43.9-68.9	5.5	53.3	27.3
ST/PB	61.1	53.3-69	3.4	59.6	14.1
BP	48.4	42.9-53.9	2.6	45.3	13.3
SS	61.1	53.1-69.1	3.8	62.9	19.0
PB	85.4	71.8-99.1	6.5	80.3	46.7
ST	55.2	50.2-60.2	2.4	53.4	17.8
WT	74.8	63.2-86.3	5.6	67.2	57.8

BP, buccopalatal technique; PB, palatobuccal technique; SS, S-shaped technique; ST, smooth typodont; WT, wrinkled typodont.

superimposed on dST. An “initial alignment” was performed by the software program, followed by a “best-fit alignment,” and then the “3D compare” function was activated. The parameters in the “color bar option” were max range=0.4 mm, min range=0.4 mm, and use of specific tolerance=±0.04 mm. The value of standard deviation (SD) was chosen from the “tabular view-3D compare.” This value (SD), calculated by the software program, indicates a mean between the positive and negative deviations resulting from each superimposition of the digital scans. For this reason, the mean among SD values was chosen to evaluate the trueness and precision.[1,48] With this procedure, a “color map” was created for visual analysis of the displacements between the superimposed digital surfaces (Fig. 3).

The accuracy of a measurement method is described by “trueness” and “precision.” Trueness refers to the closeness of agreement among the mean of a large number of test results and the reference value; precision describes the closeness of agreement among intragroup data obtained by repeated measurements.[49,50] For each experimental group, the trueness was calculated as the mean of the SD values resulting from the superimposition between each typodont and the corresponding digital reference model (dWT or dST). Differently, the precision was evaluated as the mean of SD values for each typodont and the 3D surface model that had obtained the best result of trueness after superimposition on the corresponding digital reference model in each experimental group. All the scans of the same group were superimposed on this selected 3D surface model, and the precision of each group was obtained as the mean of SD values detected by each of these superimpositions.[1,48]

Statistical analyses were performed with a statistical software program (IBM SPSS Statistics, v25; IBM Corp). To evaluate both trueness and precision, descriptive statistics (mean, standard error, median, interquartile range, 95% confidence interval) were determined. The

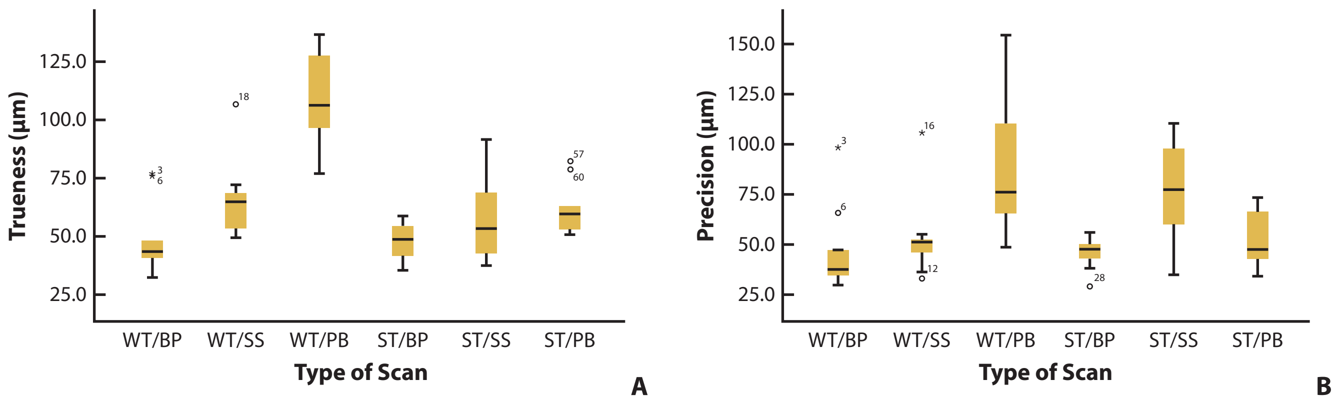

Figure 4. Box plot charts. Whiskers: minimum and maximum; Box spans: first quartile to third quartile. Median: segments inside box. Suspected outliers: unfilled circles. A, Trueness. B, Precision. BP, buccopalatal technique; PB, palatobuccal technique; SS, S-shaped technique; ST, smooth typodont; WT, wrinkled typodont.

Table 2. 2-factor ANOVA results for trueness analysis

Source	SS	Df	MS	F	*P*
Corrected model	9685.65	5	1937.13	12.59	<.001*
Intercept	55 815	1	55 815	362.76	<.001*
Typodont	1601.66	1	1601.66	10.41	.002*
Technique	6760.07	2	3380.03	21.96	<.001*
Typodont×technique	1323.90	2	661.95	4.30	.018*
Error	8308.35	54	153.85	—	—
Total	73 809	60	—	—	—
Corrected total	17 994	59	—	—	—

df, degree of freedom (n-1); MS, mean squares; SS, sum of squares. *Significant at *P*<.05.

Table 3. Results (µm) for precision: mean, lower-upper bound (95% confidence intervals), standard error, median and interquartile range

Groups	Mean	Lower-Upper Bound	Standard Error	Median	Interquartile Range
WT/BP	46.7	29.7-63.7	7.3	37.4	22.6
WT/SS	53.6	37.6-69.7	6.9	51.4	12.8
WT/PB	90	59.1-120.9	13.4	75.7	73.1
ST/BP	46	39.7-52.3	2.7	47.7	11.1
ST/SS	76	55.5-96.6	8.9	77.3	48.1
ST/PB	52.9	41.9-63.8	4.7	47.6	26.5
BP	46.4	38.3-54.4	3.8	45	15.6
SS	64.8	51.9-77.7	6.1	53.8	45.5
PB	71.5	54-88.8	8.2	65.9	31.7
ST	58.3	49-66.9	4.1	50.3	24.1
WT	63.5	50-76.9	6.5	51.4	38.3

BP, buccopalatal technique; PB, palatobuccal technique; SS, S-shaped technique; ST, smooth typodont; WT, wrinkled typodont.

Shapiro-Wilk test was used to evaluate data normality, the Levene test to evaluate the homogeneity of variances, and the 2-factor ANOVA on the ranks of the data to identify a potential interaction among typodont types and scanning techniques. The Kruskal-Wallis and the Dunn tests with the Bonferroni correction were used to analyze differences among groups (α=.05). To consider only clinically relevant comparisons, all the possible pairwise comparisons among the 6 experimental groups were not performed; consequently, whether differences existed between typodonts within a scanning technique and among scanning techniques within a typodont was evaluated.

RESULTS

The results of the analysis of trueness are summarized in Table 1 and shown in Figure 4A. Mean values were not normally distributed for all the groups, as detected by the Shapiro-Wilk test (*P*<.05). The Levene test showed homogeneity of variances (*P*=.235) for different groups. The 2-factor ANOVA (Table 2) detected statistically significant differences between the typodonts (WT versus ST) (*P*=.002), among the scanning techniques (*P*<.001), and within their mutual interaction (*P*=.018). Subsequently, the Kruskal-Wallis (*P*<.001) and the Dunn tests were run to detect any difference among the scanning techniques, and a significant difference was recorded between BP and PB (*P*<.001). The Kruskal-Wallis (*P*<.001) and the Dunn tests were run again to evaluate whether there were any statistically significant differences between typodonts within a scanning technique and among scanning techniques within a typodont, and a significant difference was detected between WT and BP versus WT and PB (*P*<.001).

The results of the analysis of precision are shown in Table 3 and Figure 4B. The mean values were not normally distributed for all the groups of scans, as detected by the Shapiro-Wilk test (*P*<.05). The Levene test determined that the variances were not homogenic (*P*=.004) for the different groups. The 2-factor ANOVA (Table 4) detected statistically significant differences among the scanning techniques (*P*=.005) and within the mutual interaction of the study variables (*P*=.009). The Kruskal-Wallis (*P*=.011) and the Dunn tests were run to identify whether there were any statistically significant

Table 4. 2-factor ANOVA results for precision analysis

Source	SS	df	MS	F	P
Corrected model	4180.83	5	836.16	4.49	.002*
Intercept	40837.50	1	40837.50	219.34	<.001*
Typodont	0.01	1	0.01	0	.992
Technique	2252.11	2	1126.05	6.04	.005*
Typodont×technique	1928.70	2	964.35	5.18	.009*
Error	8936.66	48	186.18	–	–
Total	53 955	54	–	–	–
Corrected total	13117.50	53	–	–	–

df, degree of freedom (n-1); MS, mean squares; SS, sum of squares. *Significant at $P<.05$.

Table 5. *P* values of post hoc comparisons

Compared Groups	Trueness	Precision
WT/BP-WT/SS	.268	1
WT/BP-WT/PB	<.001*	.012*
WT/SS-WT/PB	.225	.431
ST/BP-ST/SS	1	.399
ST/BP-ST/PB	.951	1
ST/SS-ST/PB	1	1
WT/BP-ST/BP	1	1
WT/SS-ST/SS	1	1
WT/PB-ST/PB	.071	.415
BP-SS	.054	.1
BP-PB	<.001*	.032*
SS-PB	.058	1

BP, buccopalatal technique; PB, palatobuccal technique; SS, S-shaped technique; ST, smooth typodont; WT, wrinkled typodont. *Statistically significant differences ($P<.05$).

differences among the scanning techniques, and a significant difference was recorded between BP and PB (P=.032). These tests were repeated (P=.005) to evaluate whether there were any statistically significant differences between typodonts within a scanning technique and among scanning techniques within a typodont, and a significant difference was detected between the means of WT and BP versus WT and PB (P=.012) (Table 5).

From the analysis of trueness from the color bar maps with the best superimposition for each group of scans, outward displacements of up to 200 μm were detected at the level of the palatal vault and rugae, regardless of the scanning technique and mostly in ST. Differently, greater inward displacements of up to 320 μm were noticed at the buccal vestibule, particularly for the PB scanning technique (Fig. 3A). For precision, outward displacements of up to 120 μm were detected on the lateral sides of the alveolar ridges in ST and at the level of the palatal vault in WT. Differently, greater inward displacements of up to 200 μm were noticed at the level of both the buccal and posterior peripheral borders, regardless of the performed scanning technique; uniquely, significant inward displacements of up to 200 μm were also noticed in the anterior left area of ST and SS (Fig. 3B).

DISCUSSION

The present in vitro study compared the accuracy of 3 different scanning techniques with one IOS (TRIOS 3 Pod; 3Shape A/S). As per the obtained results, the null hypothesis was rejected because statistically significant differences were found.

The significant difference detected between the trueness of WT and ST (P=.002) showed that the scans made on the typodont with more defined anatomic landmarks (WT) had worse trueness than those on the typodont with less defined anatomic reference points (ST). This result might seem to conflict with those of previous studies, which reported the importance of reference points to improve the accuracy of IOS in edentulous arches.[14-17,22,26,29-31] Furthermore, in the visual analysis of the color maps for trueness, outward displacements of up to 200 μm were detected at the level of the palatal rugae (Fig. 3A). However, these results do not imply that the presence of palatal rugae would lead to less accurate clinical scans of the edentulous maxilla because the software program used for the digital analysis of the superimposed scans calculated the SD value of the global displacement between the whole superimposed surfaces. For this reason, the calculated mean value was influenced by the area of the palatal rugae.

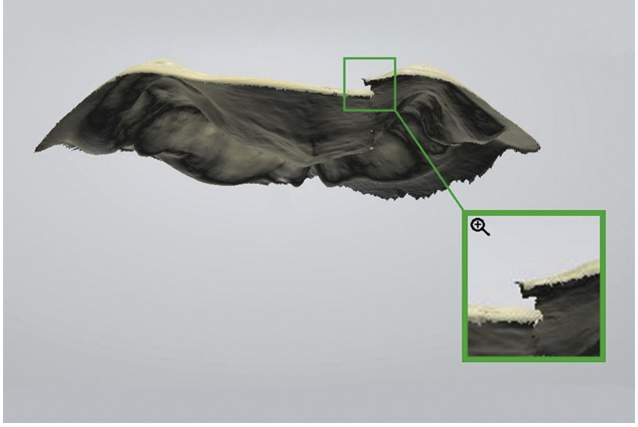

Figure 5. Displacement of palatal digital surface resulting from incorrect stitching process.

A further statistically significant difference was recorded between BP and PB for both precision (P=.032) and for trueness (P<.001). The post hoc tests also recorded a significant difference between WT and BP versus WT and PB, for both trueness (P<.001) and precision (P=.012). This result showed that the difference between BP and PB was present only on WT and could be explained by considering that in PB the palatal area was scanned before the buccal vestibule. Because the presence of palatal rugae negatively affected the stitching process of the IOS, starting from the palatal side could result in higher surface displacements (Fig. 5), determining the accumulation of matching errors during the following scanning of the buccal vestibule and ultimately altering the global accuracy of the scan.

Although significant differences were found among the tested scanning techniques, because of the experimental and comparative nature of the present investigation, the clinical impact of such differences cannot be answered unequivocally. However, using the BP scanning technique in the completely edentulous maxilla is recommended.

Limitations of the present investigation included its in vitro design, scanning polyurethane typodonts. Clinically relevant factors related to the oral environment, particularly temperature, humidity, optical features, resilience, the mobility of soft tissues, and intraoral anatomic limitations, were not modeled. Further studies, including clinical trials, involving a larger sample size should be made to support the outcomes of the present investigation.

CONCLUSIONS

Based on the findings of this in vitro comparative study, the following conclusions were drawn:

1. Scans performed on the typodont with less defined anatomic landmarks had better trueness than scans made on the typodont with more defined anatomic landmarks.
2. In the ST scenario, no differences were noticed among the 3 scanning approaches.
3. In the WT scenario, the BP scanning technique showed higher accuracy than the PB with the tested IOS, whereas SS did not show any significant difference.
4. The scanning strategy had a significant influence on the accuracy of scans of the completely edentulous maxilla.

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