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RESEARCH AND EDUCATION

Intraoral digital scans—Part 1: Influence of ambient scanning light conditions on the accuracy (trueness and precision) of different intraoral scanners

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ABSTRACT

Statement of problem. Digital scans have increasingly become an alternative to conventional impressions. Although previous studies have analyzed the accuracy of the available intraoral scanners (IOSs), the effect of the light scanning conditions on the accuracy of those IOS systems remains unclear.

Purpose. The purpose of this in vitro study was to measure the impact of lighting conditions on the accuracy (trueness and precision) of different IOSs.

Material and methods. A typodont was digitized by using an extraoral scanner (L2i; Imetric) to obtain a reference standard tessellation language (STL) file. Three IOSs were evaluated—iTero Element, CEREC Omnicam, and TRIOS 3—with 4 lighting conditions—chair light 10 000 lux, room light 1003 lux, natural light 500 lux, and no light 0 lux. Ten digital scans per group were recorded. The STL file was used as a reference to measure the discrepancy between the digitized typodont and digital scans by using the MeshLab software program. The Kruskal-Wallis, 1-way ANOVA, and pairwise comparison were used to analyze the data.

Results. Significant differences for trueness and precision mean values were observed across different IOSs tested with the same lighting conditions and across different lighting conditions for a given IOS. In all groups, precision mean values were higher than their trueness values, indicating low relative precision.

Conclusions. Ambient lighting conditions influenced the accuracy (trueness and precision) of the IOSs tested. The recommended lighting conditions depend on the IOS selected. For iTero Element, chair and room light conditions resulted in better accuracy mean values. For CEREC Omnicam, zero light resulted in better accuracy, and for TRIOS 3, room light resulted in better accuracy. (J Prosthet Dent 2020;124:372-8)

Intraoral scanning has been commonly and successfully integrated into clinical dentistry.[1-9] Digital scanning techniques are a clinically acceptable alternative to conventional impression making for tooth and implant-supported crowns and short-span fixed dental prostheses.[10-21] However, scanning accuracy has been shown to differ based on the different scanning technologies.[10,17-30] However, these studies did not analyze how lighting conditions affect scanning accuracy. A previous study has analyzed the impact of ambient scanning light conditions on the accuracy of an intraoral scanner (IOS).[29] However, only a single IOS was evaluated, and the different ambient scanning light conditions in a practice environment should be considered.[30,31]

Scanning accuracy can be affected by the scanner selected, the resolution at which the tooth is digitized, and the different fitting and smoothing algorithms that may be used to postprocess the surfaces.[2,9-20,31] Furthermore, errors may result from the individual

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Clinical Implications

The standardization of ambient lighting conditions in private practice is essential to improving the accuracy of intraoral digital scanning based on the make and model of the scanner.

choices, including calibration,[31] scanning conditions,[32,33] handling and learning,[33,34] surface characteristics,[35-38] scanning angle or scanning protocols,[21,39,40] and the reconstruction and rendering methods used, made by an operator regardless of the technology chosen.

The accuracy of the scanner is defined in ISO 5725-1 and DIN 55350-13.[41,42] Trueness relates to the ability of the scanner to reproduce a dental arch as close to its true form as possible without deformation or distortion, while precision indicates the difference among images acquired by repeated scanning under the same conditions.[12,41]

The purpose of the present in vitro study was to measure the impact of various ambient scanning light conditions on the accuracy of 3 different IOS systems. The null hypotheses were that no significant difference would be found in the digital scan accuracy (trueness and precision) of the 3 different IOSs under the 4 different ambient scanning light conditions evaluated and that no significant difference would be found in the digital scan accuracy (trueness and precision) of the 3 different IOSs under the same lighting condition.

MATERIAL AND METHODS

A dental simulator mannequin (NISSIM Type 2; Nissim) with a mandibular typodont set (Hard Gingiva Jaw Model MIS2010-L-HD-M-32; Nissim) was used. On the selected typodont, the second right premolar was missing (Fig. 1). Three marker dots (Suremark SL-10; Suremark) were added onto the mandibular typodont to aid future superimposition and 3D measurements. The markers were attached to the occlusal surfaces of the first left molar, first right premolar, and second right molar teeth (Fig. 1B). The reference typodont was then digitized as the reference model by using a structured light laboratory scanner (L2 Scanner; Imetric) to obtain a standard tessellation language (STL) file. The laboratory scanner had been previously calibrated following the manufacturer's instructions. The manufacturer of this scanner reports a trueness of <5 μm and a precision of <10 μm.

A prosthodontist (M.R.-L.) with 8 years of experience in using IOSs recorded different digital scans. To replicate the clinical environment, the interincisal opening was standardized to 50 mm. In addition, the mannequin was fixed on the head support of a dental chair, and the IOSs were always positioned on the left side of the chair. Three IOSs were evaluated (Table 1) at 4 ambient light settings (Table 2).

For the chair light (CL) group, a room with a dental chair (A-dec 500; A-dec) and no windows was selected. The LED light of the chair had an intensity of 15 000 lux and 4100 K and was oriented 45 degrees at 58 cm from the mannequin. The lighting in the room included 6 fluorescent tubes of 54 W and 5000 lumens (GE F54W-T5-841-ECO Ecolux High-Output fluorescent tube) with a white spectrum color temperature (4100 K) ceiling light and 10 000 lux measured by using a light meter (LX1330B Light Meter; Dr.Meter Digital Illuminance).

For the room light (RL) group, the light of the chair was turned off, and only the ceiling light was used, with no windows or natural light. The illuminance of the room was 1003 lux as measured by using the same light meter. For the natural light (NL) group, a room with natural light of 500 lux through windows as measured by using the same light meter was used. For the zero light (ZL) group, a room with no light and no windows was used.

Ten digital scans per system were made for each group. The control STL file was used as a reference digital model to compare the distortion with the 120 STL files obtained. The definition of trueness in the experiment was the average absolute distance between the reference model and the scanned model. The precision was defined as the distance between points of the reference model and the scanned model.[41,42] Both trueness and precision were computed from the signed distance data according to the definitions.

For the statistical analysis of the scanned models, the software package MeshLab was used to perform the geometric preprocessing of the scanned models of the typodont, and the MATLAB software program was used to postprocess the data before statistical analysis. A statistical software program (IBM SPSS Statistics, v25 for Windows; IBM Corp) was used to perform all statistical analyses.

The STL file format represented the scanned data as a triangle soup, such as a set of topologically nonconnected triangles, $\Delta_i = \{p_{i1}, p_{i2}, p_{i3}\}, i \in [1, n]$, that define the surface of the dental model. $p_{ij} \in R^3$ was the j^{th} vertex of the i^{th} triangle ($j \in \{1, 2, 3\}$). This implies that each vertex on the mesh appears more than once in the triangle soup. Each scanning process resulted in a completely different set of triangles, all representing the same physical model. For this, the coincident vertices of the triangle soup were unified to construct a topologically connected triangle mesh M(V,F). Here, $V = \{v_1, \ldots, v_n\}, v_i \in R^3$ was the set of unified vertices, and $F = \{(i, j, k)\}, i, j, k \in [1, n]$, $i \neq j \neq k$ described the triangular faces formed by the vertices (Fig. 2A). This was performed by using MeshLab.

To statistically analyze the scanned data, the primary task was to compute the spatial deviations of a treatment scanned model $S(V_s, F_s)$ with respect to the control STL model $S(V_T, F_T)$. For a vertex $v \in V_S$, the deviation was

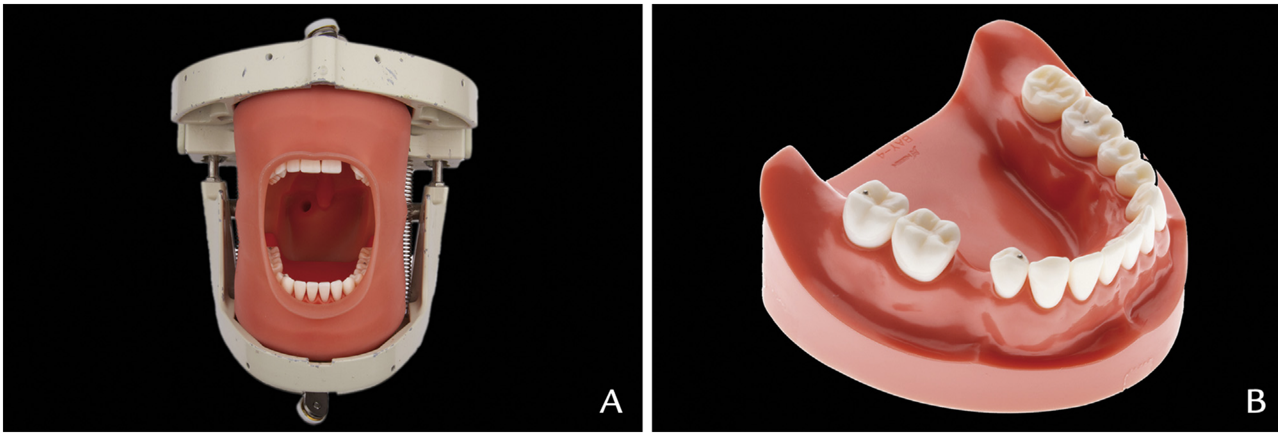

Figure 1. A, Dental simulator model with clinically standardized interincisal opening of 50 mm. B, Dentate typodont with mandibular right second premolar missing and 3 markers on occlusal surfaces on right first premolar and second molar typodont teeth.

Table 1. Characteristics of intraoral scanning systems evaluated

Group	Open/ Close System	Technology	Powdering	Color Image	Image Type
IOS-1 iTero Element (Cadent Ltd)	Open	Parallel confocal microscopy technique Illuminates the surface of the object with 3 beams of different colored light (red, green, or blue) which combine to provide white light.	No	Yes	Photography
IOS-2 Omnicam (CEREC-Dentsply Sirona)	Open	Active triangulation (multicolor stripe projection).	No	Yes	Film (video)
IOS-3 TRIOS 3 (3Shape A/S)	Open	Confocal microscopy technology. Ultrafast optical sectioning. Light source provides an illumination pattern to cause a light oscillation on the object.	No	Yes	Photography

Table 2. Summary of different light condition settings evaluated

Light Condition	Chair Light 10 000 lux 4100 K	Room Light 1003 lux 4100 K	Windows 500 lux
CL	Yes	Yes	No
RL	No	Yes	No
NL	No	No	Yes
ZL	No	No	No

CL, chair light; NL, natural light; RL, room light; ZL, zero light.

defined as the signed distance, $d_T(v)$, between v and the closest face $f \in F_T$ to v. The distance was positive if v was on the positive side of T. Mathematically, this could be computed as the sign of the dot product $\langle v - c_f, n_f \rangle$. Here, c_f and n_f were the centroid and normal of the closest face f, respectively (Fig. 2B). Given a scan S, the error metric was then defined as the set $(E(S)=\{d_T(v)\,\forall v \in V_S\})$ (Fig. 3).

For a set of multiple scanned models (S_1, …, S_n) from a given treatment population (such as IOS-1 group under chair lighting), the signed distance denoted as the set $E(B, L) = \bigcup E(S_i)$, $i \in [1, n]$ was defined as the error distribution of the whole population. Here, B is the IOS group and L is the ambient scanning light condition.

The 2 main conditions that must hold true for computing the error in the treatment scans with respect to the control scan were as follows: both S and T were open orientable surfaces. By orientable is meant that they had 2 well-defined sides. Mathematically, this implied that all triangular faces were consistently normally oriented. Also, both S and T were geometrically aligned in 3D space.

The first condition was satisfied during the vertex unification in MeshLab. For the second condition, any given intraoral scan S was first aligned with the typodont control STL_C by using the iterative closest point algorithm. This was achieved through the following steps by using the MeshLab software program (Fig. 4). First, a treatment scan was loaded along with the control mesh; second, 4 pairs of points were (approximately) chosen across the 2 meshes. Three of these 4 pairs were the spherical landmarks that were physically added. The fourth was a prominent crease landmark that could be easily identified. Finally, once the correspondence was selected, the iterative closest point algorithm was applied until convergence and was repeated until the error between the aligned meshes was minimized.

One of the key issues in performing a statistical evaluation of errors was that the scanned models from different scanners resulted in distinct boundary conditions (Fig. 5). Specifically, the outermost mesh vertices or, in other words, the ones that form the boundary of the surface were not aligned to the control mesh. Because of this, the signed distances of these vertices become extreme outliers that were not considered in the analysis. The challenge was that there was no deterministic rule

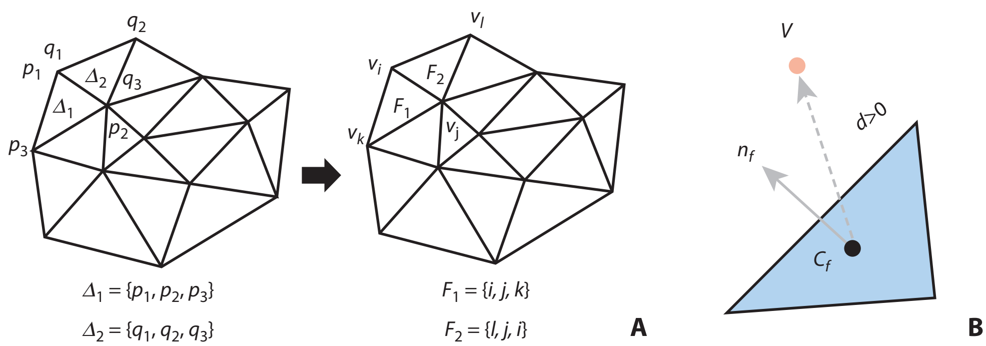

Figure 2. Geometric preliminaries for typodont scan analysis. A, Triangle soup (left) to triangle mesh (right) by using vertex unification. B, Signed distance.

on the basis of which these vertices could be identified. One option that was considered was to trim or crop vertices below a certain height from the data set. However, this was rejected because of the nonlinear geometry of the typodont.

To mitigate this issue, statistical postprocessing was performed on each given data set E(B,L) whereby extreme outliers were removed from the data set before performing statistical tests (such as ANOVA and multicomparison). The outliers were identified as error values that lie more than 3.0 times the interquartile range below the first quartile or above the third quartile.

RESULTS

For the IOS-1 group, the performance was better under the CL and RL conditions when considering the means and standard deviation of trueness and precision. For the IOS-2 group, ZL had the smallest mean and standard deviation of both trueness and precision (Table 3). For the IOS-3 group, the performance was better under NL and RL than under CL and ZL with respect to the mean and standard deviation of trueness and precision (Fig. 6).

Before conducting the ANOVA, normality testing for residuals in the ANOVA was performed by using the Kolmogorov-Smirnov test. For both precision and trueness, the result showed that the data were not normally distributed. Therefore, 2-way ANOVA could not be performed on 2 data sets. Consequently, the aligned rank transform tool (ARTool)[43] was selected to perform the aligned rank transformation on the data, and then 2-way ANOVA was conducted on the 2 data sets. The *P* value of the interaction term of the IOS and ambient scanning light conditions in 2 data sets were both lower than .05, which means there was a significant interaction effect of IOS and ambient scanning light conditions on precision and trueness. Also, the *P* value of the main effect terms of the IOS and ambient scanning light conditions in the 2 data sets were all lower than .05, which means both factors had significant main effects on precision and trueness.

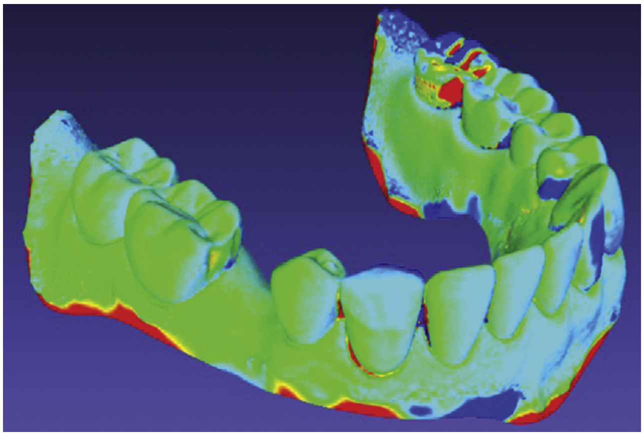

Figure 3. SEQ figure/* ARABIC 2: Color-coded signed distance field for treatment scan with respect to control mesh. *Blue* color represents areas with significantly higher dimensions, and *red* color, areas with significantly smaller dimensions.

The accuracy (trueness and precision) of ambient scanning light conditions was compared for each IOS system. Because the data were not normally distributed, the Kruskal-Wallis 1-way ANOVA was conducted for ambient scanning light conditions for each IOS individually. A pairwise comparison was also performed. The results showed that precision mean values were higher than their trueness values, which means that their relative precision was low. Moreover, by performing a pairwise multicomparison for trueness and precision for the different IOS groups (Table 4), the effect of ambient scanning light conditions on trueness was different from that on precision. In the IOS-1 group, RL and NL produced significant differences in both trueness and precision. CL and NL also produced differences in both trueness and precision. However, differences in precision were only found between RL and NL and between CL and ZL. In the IOS-2 group, significant differences in both trueness and precision were found between CL and ZL and between NL and ZL. In the IOS-3 group, significant differences in both precision

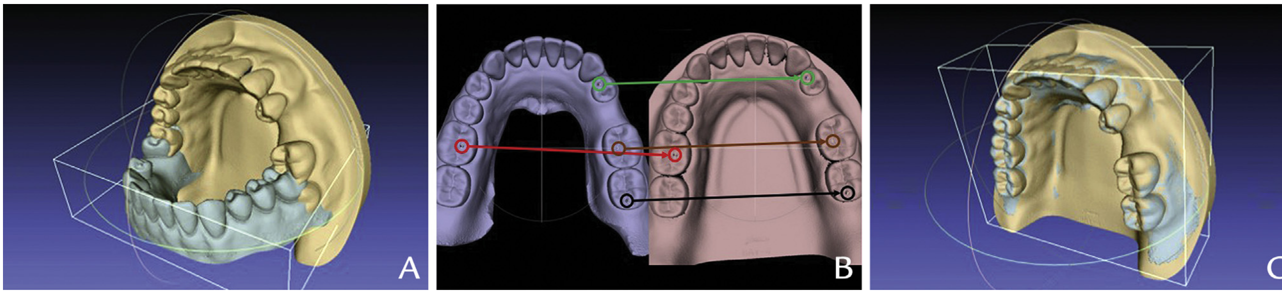

Figure 4. Typodont mesh alignment using iterative closest point algorithm in MeshLab. A, Misaligned. B, Pairs of correspondence (shown with color codes) points chosen. C, Aligned meshes after iterative closest point technique.

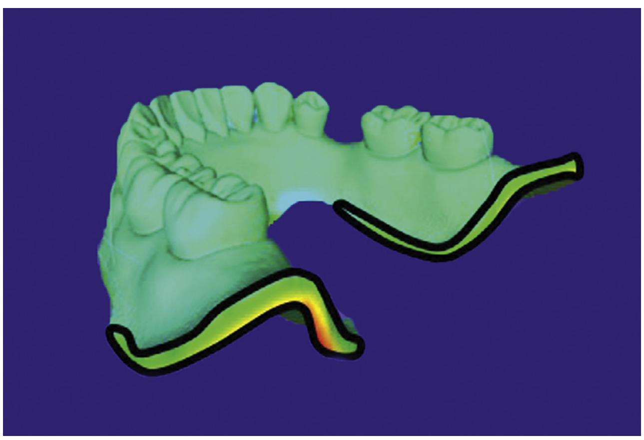

Figure 5. SEQ figure/* ARABIC 4: Extreme outliers for scanned model.

Table 3. Statistical aggregates of error for all IOS groups (IOS-1, IOS-2, and IOS-3) against lighting conditions (CL, RL, NT, ZL)

		Precision			Trueness		
Brand	Lighting	Mean	SD	Median	Mean	SD	Median
IOS-1	CL	192.81	51.56	196.13	70.96	14.53	74.51
	NL	317.24	36.91	321.65	83.22	12.47	78.50
	RL	189.83	16.19	191.85	73.46	4.68	71.97
	ZL	333.89	40.55	352.66	84.82	12.36	88.60
IOS-2	CL	533.44	277.55	438.01	408.52	129.39	393.10
	NL	545.55	180.72	475.60	445.19	135.66	370.42
	RL	431.70	234.33	384.74	326.01	112.04	315.93
	ZL	321.02	90.59	279.79	281.84	77.12	247.06
IOS-3	CL	254.40	146.69	208.19	132.69	28.73	130.99
	NL	207.65	6.75	207.70	139.49	21.61	139.26
	RL	204.48	6.34	203.86	105.59	29.00	94.31
	ZL	324.78	245.56	216.72	118.12	57.84	92.22

CL, chair light; NL, natural light; RL, room light; SD, standard deviation; ZL, zero light. Values given in micrometers.

and trueness were found between NL and ZL and significant differences in trueness only between RL and NL and between RL and CL. However, significant differences in precision were found between RL and ZL and between CL and ZL.

Comparison of accuracy (trueness and precision) was tested for each IOS system for each ambient scanning light condition evaluated. Because the data were not normally distributed, the Kruskal-Wallis 1-way ANOVA was conducted for ambient scanning light conditions for each IOS individually. A pairwise comparison was also performed. The power of the ANOVA test indicated that the size of the data sets was adequate. For trueness, except for IOS-1 and IOS-3 under ZL, all other pairs had statistically significant differences (P<.05). For precision, except for IOS-1 and IO-3 under RL and CL and IOS-1 and IOS-3 under ZL, all other pairs had statistically significant differences (P<.05).

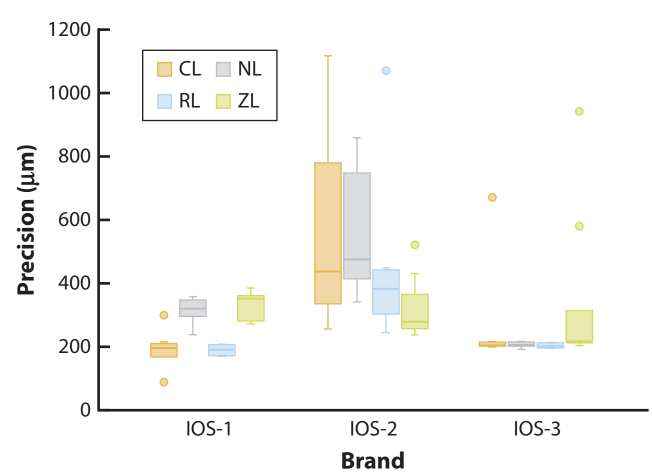

Figure 6. Boxplot of minimum, maximum, interquartile range, medians, and outliers for trueness and precision of different IOSs and ambient scanning light conditions. CL, chair light; IOS, intraoral scanner; NL, natural light; RL, room light; ZL, zero light.

DISCUSSION

Significant differences were found among the 3 IOS systems tested under the same ambient scanning light conditions, and significant differences were found among the 4 scanning light conditions while using the same IOS system; consequently, the null hypotheses were rejected. Dental studies that analyzed the impact of different ambient light conditions on the accuracy of intraoral digitizer systems are scarce.[42] However, this

Table 4. Power of ANOVA test of trueness and precision by IOS groups (IOS-1, IOS-2, and IOS-3) and light conditions (CL, IOS, NL, RL, ZL)

	CL		NL		RL		ZL	
Sample 1/Sample 2	Trueness	Precision	Trueness	Precision	Trueness	Precision	Trueness	Precision
IOS-1/IOS-2	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.334
IOS-1/IOS-3	0.038	0.121	0.015	0.009	0.015	0.223	0.310	0.006
IOS-2/IOS-3	0.031	0.007	0.010	0.000	0.010	0.001	0.002	0.071

CL, chair light; NL, natural light; RL, room light; ZL, zero light.

scanning-based error has been analyzed previously in engineering studies.[44-47]

Recommendations for the optimal operating light in a dental operatory are scarce.[48-50] In 1979, Viohl[48] described 500 lux as ideal room light condition and 2500 lux for the dental chair illumination. In 2011, the European Standard for Illumination (EN 12464) recommended 500 lux for general illumination, 1000 lux in the medical or examination rooms, and 10 000 lux for the operating cavity.[49] In the present study, the chair, room, and natural light illumination were in accordance with the recommended European Standards.

Based on the present in vitro study, ambient light conditions significantly influenced the accuracy of all IOSs tested. For iTero Element, CL and RL led to better trueness and precision mean values than the other light conditions tested; for the CEREC Omnicam, ZL scanning conditions presented the better trueness and precision mean values; and, for the TRIOS 3, RL scanning conditions produced better trueness and precision mean values. However, the NL conditions evaluated did not provide the highest accuracy when using the IOSs tested.

Scanning accuracy differences based on the different scanning technologies were identified in previous studies.[10,18-27,41-48] Both iTero Element and TRIOS 3 IOSs use the parallel confocal imaging technique.[22] However, while the RL resulted in the best accuracy mean values with both systems, iTero Element performed marginally better under CL. However, CEREC Omnicam IOS system uses a triangulation technique, with better accuracy under ZL.

The present study showed that precision mean values in all groups were higher than their trueness values, indicating that their relative precision was low. Previous studies that have analyzed the accuracy of the digital scans performed by using different IOS systems[10-28,44-48] have not provided analysis on how lighting conditions affect scanning accuracy, which makes the accuracy values reported questionable. Additionally, the different methodology used made comparisons between the available studies difficult because of the complexity and area of the geometry analyzed (prepared tooth, sextant, or complete arch), superimposition method selected (best-fit algorithm or iterative closest point algorithm), and/or reference model used.

Arakida et al[29] evaluated the influence of the illuminance (0, 500, and 2500 lux) and color temperature (3900, 4100, 7500, and 19 000 K) of the lighting on the accuracy of scans made by using the True Definition IOS. The 500 lux and 3900 K obtained the highest accuracy, but the numerical values are not comparable with those of the present study as a different technology was used, only 2 teeth were digitized, and the reference model was an STL file obtained through a CMM machine.

The results of this study were obtained by performing a digital scan on a completely dentate arch in an in vitro environment. Evaluations of other clinical scenarios by using IOSs may, however, change the outcome because of inaccuracies from edentulous areas with a higher level of nonattached tissues. Further studies are needed to fully understand the impact of lighting conditions on the accuracy of the available intraoral digitizer systems in the clinical environment.

CONCLUSIONS

With the limitations of this in vitro study, the following conclusions were drawn:

1. Lighting conditions influenced the accuracy (trueness and precision) of the digital scans performed by using any of the 3 intraoral scanners tested.
2. An ideal lighting condition that resulted in the best accuracy for all scanning technologies was not found.
3. Consequently, lighting condition should be selected based on the specific IOS system used.
4. For the iTero Element scanner, chair (10 000 lux) and room (1003 lux) lighting improved the trueness and precision mean values.
5. For the CEREC Omnicam scanner, zero lighting resulted in better trueness and precision mean values.
6. For the TRIOS 3 scanner, room (1003 lux) lighting provided better trueness and precision mean values.

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