Influence of Luminosity on the Precision and Accuracy of Intraoral Scanning: A Comparative *in vitro* Study

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ABSTRACT

Objectives: This in vitro study focused on verifying the influence of different ambient light conditions on the accuracy and precision of models obtained from digital scans. Methodology: To measure the tested illuminances: chair light/reflector; room light, and natural light at the time of scanning, a luxmeter was used. From the STL file, nine experimental groups were formed. Results: Of the nine specific combinations between the three IOS and the three types of lighting, it was verified that for all of them, as well as the ICC, the accuracy was also excellent, in which the measured values were not significantly influenced by the IOS brand (p = 0.994) nor by the type of lighting (p = 0.996). For precision data, GLM indicated a statistically significant interaction between IOS and lighting type. Under LS, accuracy was significantly higher with 3Shape® than with CS 3600 CareStream®, which had significantly higher accuracy than Virtuo Vivo™ Straumann®. Conclusions: The models obtained with the three IOS evaluated exhibited excellent accuracy under the different illuminance tested and the 3Shape® under the three illuminance conditions was the device that presented the best precision, specifically when using LC and LS.

INTRODUCTION

The rehabilitation of patients without teeth using implant-supported fixed prostheses is a reliable treatment.[1] However, it is necessary to make passive adjustments to prevent biomechanical complications that could jeopardize the long-term success of the implants and prostheses.[2,3,4] To achieve this, it is important to minimize distortions in conventional impressions or intraoral scans, ensuring that they are below the clinically acceptable mismatch of 10 to 150 µm for linear measurements, as reported in the literature.[5,6,7,8,9]

Intraoral digital scans are a suitable method for molding single and few-element implant-supported fixed prostheses.[10] Intraoral scanners (IOS) are a well-established alternative to conventional molding for achieving a passive fit of the prosthesis.[11-15] They offer greater patient comfort by avoiding harmful stimuli such as choking and irritation of the palate, and also reduce clinical treatment time and increase ease of performance[6,8,13,16,17] It reduces the distortion of impression materials and allows for three-dimensional (3D) previews of the preparation.[8,13,17]

When combined with Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), intermediate steps in the laboratory that are prone to human errors and material variations can be avoided.[14,16,18,19]

Research conducted in the past five years on IOS has primarily focused on accuracy, which is defined by the International Organization for Standardization (ISO 5725-1) as a combination of 'precision' and 'trueness'. Trueness is described as the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. Precision refers to the degree of agreement among test results obtained under stipulated conditions (ISO, 2022).[20]

However, the results of full arc scans (AC) are heterogeneous, with a reported distortion range between 17 and 378 μm.[17,21,22] In addition to the IOS itself, regular calibration is a contributing factor that can influence the accuracy of a scan.[23] However, studies[14,17,24,25,26] have concluded that only a few devices benefit from a specific standard for AC scans. In addition, it is worth noting that the operator's experience may improve the required scanning time, but not the accuracy when using a newer IOS.[27] Furthermore, since all scanners are based on optical imaging methods, another potential influencing factor is the ambient light in dental offices. It is important to consider this when interpreting results.[13,28-37]

Proper lighting for a dental clinic requires multiple zones of illuminance to balance work and ambient lighting.[37] According to European Lighting Standards, the oral cavity, as a visual work area, should be illuminated with a minimum of 5,000 lux. An illuminance of at least 1,000 lux is suggested for an area of 1.5 square meters around the patient, while all other areas require an illuminance of 500 lux or more (ECS, 2019). If the light contains all visible wavelengths in a balanced proportion, it is equivalent to daylight, with a color temperature of 5,500 to 6,000 Kelvin. If the light contains all visible wavelengths in a balanced proportion, it is equivalent to daylight, with a color temperature of 5,500 to 6,000 Kelvin. This lighting is most suitable for visual color selection.[38]

Digital scans have become an increasingly popular alternative to conventional molds. Although previous studies[10,13, 28-37] have analyzed the effect of illuminance conditions on the accuracy of some IOS, it is still unclear which of these systems and which type of lighting is recommended for obtaining accuracy in AC.

This *in vitro* study focuses on verifying the influence of different ambient light conditions on the accuracy and precision of models obtained from digital scans by three intraoral scanners in a complete mandibular arch.

METODOLOGY

A dental mannequin head (Pronew, Odonto Carapiá Ind. e Com. de Prod. Odontológicos Ltda., São Gonçalo-RJ, Brazil) with complete upper and lower arches, and articulation, was used. In addition, the mannequin was fixed on the head support of a dental chair, and the IOS was positioned on the left side of the chair. For this study, the lower arch was chosen as the standard to be scanned by the different scanners.

To create the study groups, a Lux Meter (Digital Lux Meter MLM-1011, Minipa do Brasil Ltda.,) was required. The Lux Meter aimed to measure the ambient illuminance during scanning using three different types of lighting. For the natural light (500-lux) group a room with natural window light was selected. For the remaining groups no windows was used, where 2 main light sources were available: namely the room ceiling light and the chair light. For the room light (LS, 1,003 lux) 6 fluorescent tubes of 54 W, 5000 lm (GE F54W-T5–841-ECO; Ecolux High Output) with a white spectrum color temperature (4100 K) ceiling light was selected and the chair light was turned off. Chair/reflector light (LC, 10,000 lux) group the ceiling light was turned on and distance between the chair light and the mannequin, always oriented 45° from the mannequin, was varied to adjust the luminosity at the dental mannequin (*Table 1*).

Table 1. iOS and illuminance values from the experiment with study group formation.

IOS	Illuminance	acronym	Grup	Lux
1. Virtuo Vivo Straumann®	Chair light/ reflector	LC	St-LC	10.000
	Room light	LS	St-LS	1.003
	Natural Light	LN	St-LN	500
2. CS 3600 CareStream®	Chair light/ reflector	LC	CS-LC	10.000
	Room light	LS	CS-LS	1.003
	Natural Light	LN	CS-LN	500
3. 3Shape TRIOS®	Chair light/ reflector	LC	Sh-LC	10.000
	Room light	LS	Sh-LS	1.003
	Natural Light	LN	Sh-LN	500

Legend: IOS (intraoral scanner); LC (chair light/reflector); LS (room light); LN (natural light); St (Virtuo Vivo Straumann®); CS (CS 3600 CareStream®); Sh (3Shape TRIOS®); ™ (trademark).

The extraoral scanner HandyScan 700 3D from the engineering company Kreo was selected for virtual scanning of the master model, which will serve as a reference for comparison to the standard STL. This standard model will be compared to models scanned using three other intraoral scanners (IOS): Virtuo Vivo™ Straumann® (Virtuo Vivo scanner intraoral; Straumann) AG), CS 3600 CareStream® (Carestream, USA), and 3Shape TRIOS® (3 shape Trios 4, Copenhagen, Dinamarca). All the experimental scans were acquired by a prosthodontist with 5 years of previous experience handling IOSs (S.W.A.V).

Using the scanned file in STL format, we obtained the standard model as a reference to measure the discrepancies between the scans obtained with the three IOS devices under three different ambient light conditions. This formed the basis for the experimental groups (n=9) *(Table 2*). The standard model and experimental virtual models were then uploaded to the Polyworks software (Kreo Metrology).

The comparison began by using the reference model with a certified high-precision extraoral volumetric scanner of 25 µm (HandyScan 700 3D). The first scan of the sample (standard model) was performed with this scanner *(Figure 1*). All other samples were compared to the standard model, as it is the only scanner with certified calibration based on ISO 10360 standards.

The experimental samples underwent the Best-Fit Alignment process, which involved aligning the standard model with each model obtained from the different IOS tested under varying lighting conditions. The experimental samples underwent the Best-Fit Alignment process, which involved aligning the standard model with each model obtained from the different IOS tested under varying lighting conditions. This alignment process minimizes the distances between all captured points in both scans. The software can be used to create a color scale to visualize the differences between the two models using a color map.

Table 2. Accuracy measures and averages (mm) found at the six points of each group (IOS in relation to illuminance) on the X and Y axes.

Grups	Axes X				Mean	Axes Y		Mean
	pt 1	pt 2	pt 3	pt 4	pt X	pt 5	pt 6	pt Y
St-LC	-0,24	-0,14	-0,25	-0,13		0,12	-0,11	
St-LS	-0,88	-0,59	-0,68	-0,48		0,29	-0,39	
St-LN	-0,27	-0,23	-0,30	-0,18		0,07	-0,05	
Mean	-0,46	-0,32	-0,41	-0,26	-0,36	0,16	-0,18	-0,01
CS-LC	-0,10	0,01	-0,11	-0,29		-0,67	-0,28	
CS-LS	-0,16	-0,09	-0,23	-0,35		-0,35	-0,32	
CS-LN	-0,17	-0,06	-0,15	-0,24		-0,42	-0,16	
Mean	-0,14	-0,05	-0,16	-0,29	-0,16	-0,48	-0,25	-0,37
Sh-LC	0,06	0,07	-0,01	-0,04		-0,08	-0,06	
Sh-LS	-0,05	0,00	-0,13	-0,14		0,15	-0,03	
Sh-LN	-0,24	-0,22	-0,28	-0,21		-0,02	-0,02	
Mean	-0,08	-0,05	-0,14	-0,13	-0,10	0,02	-0,04	-0,01

Legend: pt (point, measured with virtual caliper); St (Virtuo Vivo™ Straumann®); LC (chair light/reflector, 10,000 lux); CS (CS 3600 CareStream®); Sh (3Shape TRIOS®); LS (room light, 1,003 lux); LN (natural light, 500 lux); - (minus).

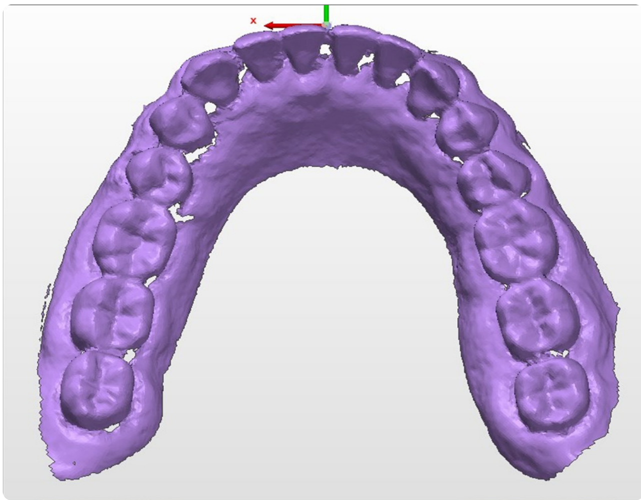

Figure 1: A virtual scan of the reference model (standard).

At this point, some general deviations can be observed. However, since the Best-Fit alignment minimizes all differences, this is not a fair comparison. To eliminate all errors, it was necessary to align the Reference Point System (RPS), which minimizes distances in all 6 degrees of freedom, only at six points on the X and Y axes, making it easy to observe the deviations. With the RPS alignment, surface distances in the X, Y, and Z directions were zeroed to achieve a fair alignment, resulting in a new color map *(Figure 2*).

The dispersion and deviations from the reference model were measured using a virtual caliper to determine distances in the X and Y directions. The dispersion and deviations from the reference model were measured using a virtual caliper to determine distances in the X and Y directions. The Z direction was found to be too small and all deviations were outside the tolerance range of the HandyScan 700 3D. The dispersion and deviations from the reference model were measured using a virtual caliper to determine distances in the X and Y directions. Nominal distance refers to the distance found in the reference sample, while the distance found in each IOS under study was 45 cm.

The data was analyzed by the IOS under different lighting conditions and correlation of the IOS under different illuminations. The data was analyzed by the IOS under different lighting conditions and correlation of the IOS under different illuminations. Each IOS value was recorded in relation to illuminations, and each illumination value was recorded in relation to IOS.

The data was analyzed by the IOS under different lighting conditions and correlation of the IOS under different illuminations. To verify accuracy, the groups were analyzed at six points on the X and Y axes. These values were measured using a virtual caliper, with the Metrology Grade Scanner HandyScan 700® 3D software.

To assess accuracy, each value in Table 2 (IOS in relation to illuminances) and Table 3 (illuminances in relation to IOS) represents the difference between the nominal value or reference of each sample collected in the composition of the groups, as measured by the software.

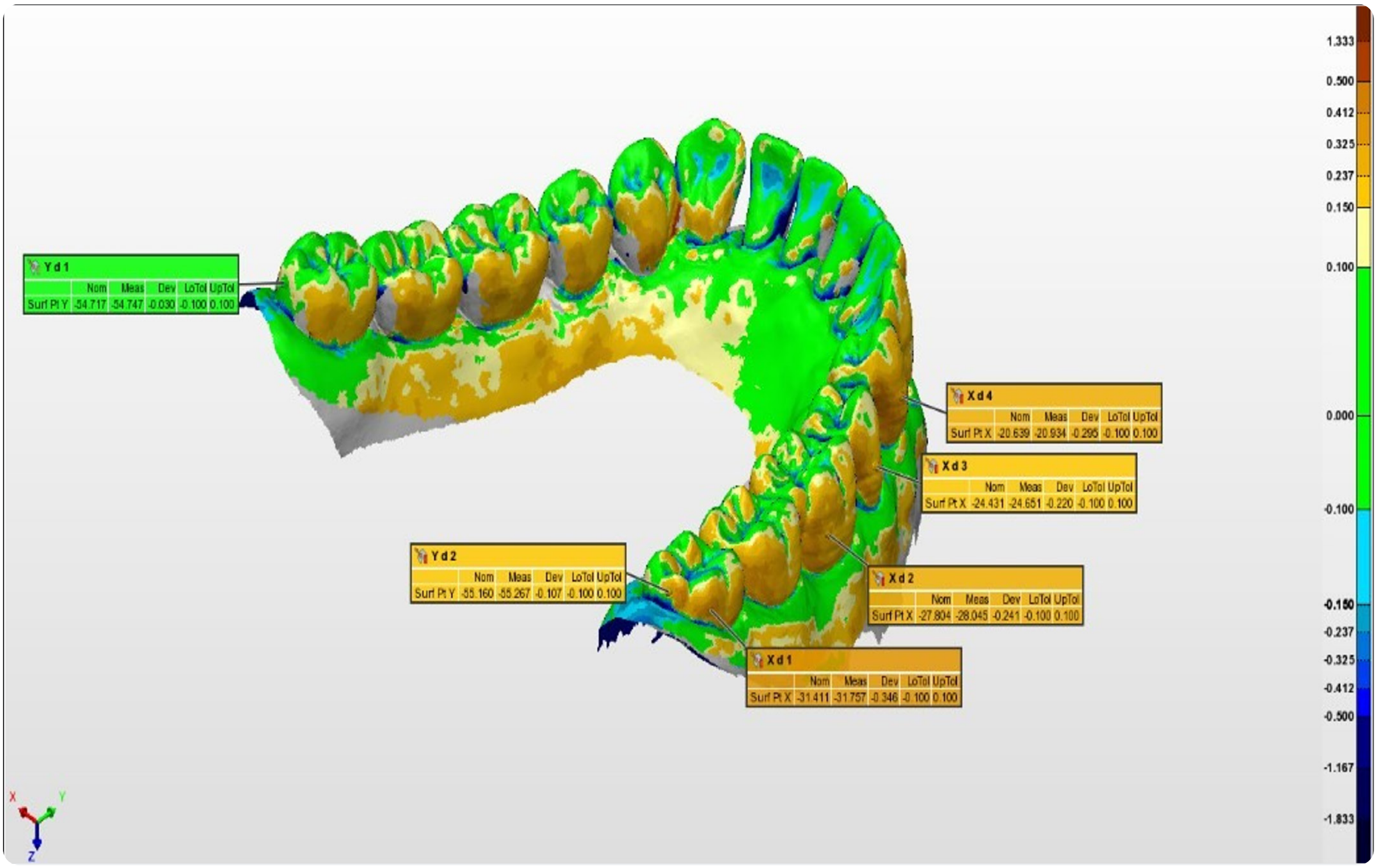

Figure 2: Overlap of the standard model and the IOS model with six points on the X and Y axes, aligned with RPS on the color scale.

Table 3. Accuracy measures and means (mm) found at the six points of each group (illuminance in relation to the IOS) on the X and Y axes.

Grups	Axes X				Mean	Axes Y		Mean
	pt 1	pt 2	pt 3	pt 4	pt X	pt 5	pt 6	pt Y
St-LC	-0,24	-0,14	-0,25	-0,13		0,12	-0,11	
CS-LC	-0,10	0,01	-0,11	-0,29		-0,67	-0,28	
Sh-LC	0,06	0,07	-0,01	-0,04		-0,08	-0,06	
Mean	-0,09	-0,02	-0,12	-0,15	-0,10	-0,21	-0,15	-0,18
St-LS	-0,88	-0,59	-0,68	-0,48		0,15	-0,03	
CS-LS	-0,16	-0,09	-0,23	-0,35		-0,35	-0,32	
Sh-LS	0,05	0,00	-0,13	-0,14		0,15	-0,03	
Mean	-0,33	-0,23	-0,35	-0,32	-0,31	-0,02	-0,13	-0,07
St-LN	-0,27	-0,23	-0,30	-0,18		0,07	-0,05	
SC-LN	-0,17	-0,06	-0,15	-0,24		-0,42	-0,16	
Sh-LN	-0,24	-0,22	-0,28	-0,21		-0,02	-0,02	
Mean	-0,23	-0,17	-0,24	-0,21	-0,21	-0,12	-0,08	-0,10

Legend: pt (point, measured with virtual caliper); St (Virtuo Vivo™ Straumann®); LC (chair light/reflector, 10,000 lux); CS (CS 3600 CareStream®); Sh (3Shape TRIOS®); LS (room light, 1,003 lux); LN (natural light, 500 lux); - (minus).

To evaluate the accuracy of the models obtained by the three tested IOS under different lighting conditions compared to the measurements recorded in the standard model with the extraoral scanner, was applied the intraclass correlation coefficient (ICC) and the generalized linear model (GLM). Was used the GLM approach for the precision data, which were further subjected to the Tukey test. Three scans of each group were repeated by the same professional after one week and the differences in measurements in relation to the standard model were performed and Intra observer agreements were determined by calculating the unweighted kappa coefficients. The statistical calculations were performed using SPSS 23 software (SPSS Inc., Chicago, IL, USA), with a significance level set at 5%.

RESULTS

Focusing on each of the three IOS, regardless of the type of lighting used, ICC revealed that the accuracy of the tested devices in relation to the extraoral scanner was excellent *(Table 4*). The same degree of accuracy was found when evaluating each of the lighting conditions, regardless of which of the three IOS was used *(Table 5*). After calculating Cohen's kappa, we found a very good intraobserver-agreement level concerning t (κ = 0.885)

For the standard model (extraoral scanner), the average measurement obtained at the evaluation points was 56.52 ± 5.37 μm . Identical uppercase letters indicate no significant difference between IOS (within each column). Identical lowercase letters indicate no significant difference between lighting types (within each row).

Table 4. Means (±) of accuracy measurements (mm) obtained at six evaluation points for models and CCI results for IOS and illuminance compared to the standard model.

IOS e illuminance	Mean (mm)	CCI (IC 95%)	Accuracy
St	56,77 ± 5,12[A]	0,998 (0,993-0,999)	Excellent
CS	56,75 ± 4,97[A]	0,998 (0,996-0,999)	Excellent
Sh	56,59 ± 5,03[A]	1,000 (0,999-1,000)	Excellent
LC (10.000 lux)	56,64 ± 5,01[a]	0,999 (0,998-1,000)	Excellent
LS (1.003 lux)	56,67 ± 5,02[a]	0,999 (0,998-1,000)	Excellent
LN (500 lux)	56,79 ± 5,09[a]	0,997 (0,993-0,999)	Excellent

Table 5. The average accuracy measurements (in mm) obtained at the six evaluation points for the groups (IOS under different illuminations) and the CCI results in relation to the standard model.

IOS		Type of lightening		
		LC	LS	LN
St	Mean (mm)	56,54 ± 5,40[Aa]	56,68 ± 5,41[Aa]	56,97 ± 5,52[Aa]
	CCI (IC 95%)	0,999 (0,995-1,000)	0,999 (0,994-1,000)	0,951 (0,995-0,999)
	Accuracy	Excellent	Excellent	Excellent
CS	Mean (mm)	56,76 ± 5,27[Aa]	56,67 ± 5,29[Aa]	56,72 ± 5,33[Aa]
	CCI (IC 95%)	0,998 (0,982-0,999)	0,999 (0,987-0,999)	0,999 (0,991-0,999)
	Accuracy	Excellent	Excellent	Excellent
Sh	Mean (mm)	56,53 ± 5,33[Aa]	56,55 ± 5,34[Aa]	56,69 ± 5,39[Aa]
	CCI (IC 95%)	0,999 (0,999-1,000)	0,999 (0,998-1,000)	0,999 (0,994-1,000)
	Accuracy	Excellent	Excellent	Excellent

For the standard model (extraoral scanner), the average measurement obtained at the evaluation points was 56.52 ± 5.37 mm. Identical uppercase letters indicate no significant difference between IOS (within each column). Identical lowercase letters indicate no significant difference between lighting types (within each row).
Legend: Intraoral scanners (IOS); millimeter (mm); intra-class correlation coefficient (CCI); confidence interval (CI); percentage (%); standard deviation (±); Virtuo Vivo™ Straumann® (St); CS 3600 CareStream® (CS); 3Shape TRIOS® (Sh); chair light (LC); room light (LS); natural light (LN).

Focusing on each of the nine specific combinations between the three IOS and the three types of lighting, it was found that for all of them, as well as the ICC, the accuracy remained excellent (*Table 5*). In fact, the measured values were not significantly influenced by the brand of the IOS (p = 0.994) or the type of lighting (p = 0.996), as shown in Tables 3 and 4.

For the precision data, GLM indicated a statistically significant interaction between IOS and lighting type (p = 0.05). When applying the Tukey test to understand this interaction, it was observed that under LN (500 lux), there was no significant difference in the precision conferred by the three IOS. Under LS (1,003 lux), the precision was significantly higher with the 3Shape TRIOS® IOS than with the CS 3600 CareStream®, which had significantly higher precision than Virtuo Vivo™ Straumann®. However, the IOS 3Shape TRIOS® showed significantly higher precision than the CS 3600 CareStream® when LC (10,000 lux) was used, which was the condition in which it had the highest precision *(Table 6)*.

Continuing with the interpretation of the interaction for precision data, it was found that only the CS 3600 CareStream® was not significantly affected by the type of lighting. For the Virtuo Vivo™ Straumann®, precision under LS (1.003 lux) was significantly lower than that obtained under LC (10,000 lux) and LN (500 lux), with no difference between these last two lighting conditions. When using 3Shape TRIOS®, the precision was significantly higher when the light source was from the chair/reflector (LC, 10,000 lux) or the room (LS, 1,003 lux), with no significant difference between them, compared to LN (500 lux), which had significantly lower precision *(Table 6, Figure 3)*.

Table 6. Means precision (mm) of models obtained by IOS was evaluated in six points in relation to the standard model, considering the type of lighting.

IOS	Type of lightening		
	LC	LS	LN
St	-0,13 ± 0,13[Ba]	-0,46 ± 0,40[Cb]	-0,16 ± 0,14[Aa]
CS	-0,24 ± 0,24[Ca]	-0,25 ± 0,11[Ba]	-0,20 ± 0,12[Aa]
Sh	-0,01 ± 0,06[Aa]	-0,03 ± 0,11[Aa]	-0,17 ± 0,11[Aa]

Capitalized letters indicate no significant difference between IOS (within each column). Lowercase letters indicate no significant difference between lighting types (within each row). Legend: IOS (intraoral scanners); mm (millimeter); CCI (intra-class correlation coefficient); CI (confidence interval); % (percentage); ± (standard deviation); St (Virtuo Vivo™ Straumann®); CS (CS 3600 Carestream®); Sh (3Shape TRIOS®); LC (chair/reflector light); LS (room light); LN (natural light).

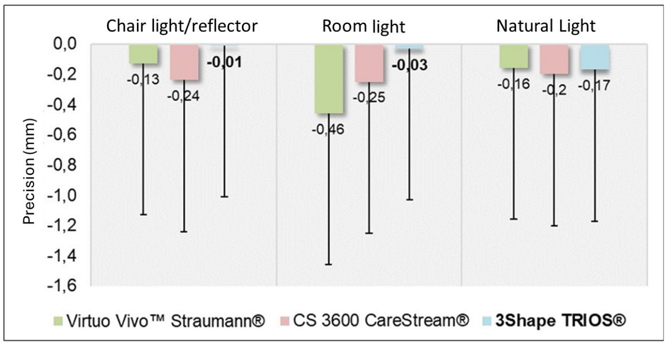

Figure 3: Column chart of average values (mm) for the accuracy of models obtained by IOS, according to the type of lighting, in relation to the standard model.

DISCUSSION

Accuracy in intraoral scanning is essential as it influences the prognosis of restorations. In this study, the workflow was performed on a mandibular dental mannequin. Therefore, it is necessary to consider the variability of results, as stated in ISO 5725-1, which indicates that precision in materials presumed to be identical in presumably identical situations does not generally produce identical results. In the practical interpretation of measurement data, it is important to consider this variability (ISO, 2022).[20]

The STL model of the mandibular AC in this study was obtained using the high-precision HandySCAN 700® 3D extraoral scanner with certified volumetric accuracy of ± 0.025 µm (± 25 µm). In the study by Arakida *et al.* (2018),[13] the master data was acquired using a 3D CMM Infinite Focus G5® with an accuracy of 5.3 ± 1.1 µm and a precision of 1.6 ± 0.6 µm. Revilla-León *et al.* (2020c),[30] Koseoglu *et al.* (2021),[34] Wesemann *et al.* (2021)[37] and Ochoa-López *et al.* (2022)[10] digitized the E4 Dental 3Shape® working model with a precision value of 4 µm. Jivanescu *et al.* (2021)[33] used the 3D D700 3Shape® extraoral scanner with a precision value of < 20 µm. Revilla-León *et al.* (2020a, 2021)[28,32] selected the L2i Scanner® with an accuracy value of < 5 µm and a precision value of < 10 µm.

Thus, the comparison with other studies is limited due to methodological plurality. In this study, the Best-Fit alignment method was used with model overlay using six points on the X (4 points) and Y (2 points) axes in 6 degrees of freedom, followed by RPS alignment, resulting in new color maps. Using a similar method, Jivanescu *et al.* (2021)[33] utilized the Geomagic Control X 3D software to align the mandibular AC models. They employed the Best-Fit alignment method followed by the RPS alignment method to ensure precise alignment. A color-coded map was generated to display surface deviation patterns, revealing deviations of ±100 µm. The Best-Fit algorithm was also used by Arakida *et al.* (2018).[13] However, the distances measured (in µm) of the models were determined by calculating the mean of the 90th and 10th percentiles and analyzed using CAD software (CATIA V5®). Koseoglu *et al.* (2021) also used the Best-Fit algorithm, combining the defined models with an acceptability limit of 100 µm, and analyzed the results using Geomagic Control X® 3D software.

When comparing digital maxillary impressions to conventional *in vitro* and in vivo impressions, Keul & Güth (2020)[14] found that the direct scanning method using iTero Element® had higher precision in six out of eight *in vitro* measurement parameters and seven out of eight in vivo measurement parameters. The indirect scanning method had the best precision in five out of eight *in vitro* measurement parameters. Cechelero *et al.* (2021)[26] demonstrated that when overlapped and compared, scans captured more meshes using extraoral scanners compared to IOS techniques. Although Medina-Sotomayor *et al.* (2018a)[17] did not find a correlation between better resolution and accuracy in an impression of AC with the 3Shape TRIOS® with a resolution of 41.21 points/mm², a subsequent study (Medina-Sotomayor *et al.*, 2018) is needed to confirm these findings. In 2018b,[8] it was made clear that although there is a higher density of points, they are not adequately filtered and ordered to obtain a 3D image with the accuracy of the real model. it was made clear that although there is a higher density of points, they are not adequately filtered and ordered to obtain a 3D image with the accuracy of the real model.

The accuracy of an intraoral scan can be influenced by various factors, such as the presence of saliva and blood, movement of soft tissues, the geometry of a preparation, operator experience, and the limited space that the oral cavity allows for camera maneuvering. However, there is another potentially important influencing factor related to the ambient light condition (ISO, 2022). Only a few *in vivo* and *in vitro* studies[10,13,28-31,33,34] have evaluated the impact of different lighting sources on the accuracy of the models, which prompted the conduction of this *in vitro* study on mandibular AC.

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In this *in vitro* study of mandibular AC scans, using Virtuo Vivo™ Straumann®, CS 3600 CareStream®, and 3Shape TRIOS® IOS under LC (10,000 lux), LS (1,003 lux), and LN (500 lux) lighting, the accuracy values were not significantly influenced by the IOS brand (p = 0.994) or the type of lighting (p = 0.996). The mean values ranged from 56.53 ± 5.33 μm; ICC 0.999 (3Shape TRIOS® under LC, 10,000 lux) to 56.97 ± 5.52 μm; 0.951 (Virtuo Vivo™ Straumann® under LN, 500 lux) (*Tables 4 and 5*), demonstrating excellent accuracy for the variables (IOS and illuminance). In terms of accuracy, at LS (1.003 lux), the value was significantly higher with the IOS 3Shape TRIOS® (-0.03 ± 0.11 mm) than with the CS 3600 CareStream® (-0.25 ± 0.11 mm), which was significantly higher than with the Virtuo Vivo™ Straumann® (-0.16 ± 0.14 μm). However, under LC (10,000 lux), Virtuo Vivo™ Straumann® (-0.13 ± 0.13 μm) showed significantly higher values than CS 3600 CareStream® (-0.24 ± 0.24 μm). In this condition, IOS 3Shape TRIOS® showed significantly higher precision (-0.01 ± 0.06 μm) (*Table 6, Figure 1*).

In the realm of technological advancement, the majority of contemporary systems are predicated upon 3D reconstruction technologies utilizing structured light. This methodology encompasses the imaging and capture of deformations in a projected light pattern as it interacts with the dental arch. Such an approach is foundational to the predictive modeling of learning curves associated with both wired and wireless intraoral scanners.[35] Moreover, the influence of scanning technologies extends to the realm of digital impressions, significantly impacting their accuracy and reliability.[36] The operational principles of the intraoral scanning systems (IOSs) examined in the current study diverge markedly. These systems are predicated on distinct technological principles, including confocal microscopy (Trios), LED light scanner with Active Speed 3D video technology (CS 3600 CareStream®), and Blue laser-based Multiscan imaging technology (Virtuo Vivo™ Straumann®). Such differentiation in foundational technology may elucidate the observed discrepancies in precision, particularly noting that the Virtuo Vivo™ Straumann® exhibits significant variations in accuracy under different lighting conditions.

In a series of *in vitro* and *in vivo* studies, Revilla-León *et al.* (2020a,b,c,d, 2021)[28-32] using the same protocol for maxillary AC and QD scans, the first being an *in vitro* study on maxillary AC (2020a), the three IOS systems tested (iTero Element®, CEREC Omnicam®, 3Shape TRIOS®) showed that 3Shape TRIOS® provided higher accuracy and precision values under 1.003 lux (LS: 105.59 ± 29.00 μm and 204.48 ± 6.35 μm, respectively). The authors concluded that the lighting condition should be selected based on the specific IOS system used. In the *in vivo* study, using only the IOS 3Shape TRIOS® (2020c), the best accuracy values were obtained in AC under LS (1.003 lux: 73.22 ± 199.42 μm), and the lowest precision values were observed in QD under LC (10,000 lux: 60.78 ± 131.15 μm) when compared to the other lighting conditions. Therefore, it was concluded that depending on the extent of the scans, lighting conditions had different influences. In their latest study, Revilla-León *et al.* (2021)[32] quantified the impact of lighting on the accuracy of mandibular AC scanning with the 3Shape TRIOS® *in vitro*. They found the lowest discrepancy under LS (1.003 lux), with a median of 26.33 μm and an IQR of 40.04 μm (11.97-52.00 μm) (p < 0.001). Therefore, they recommend using the 3Shape TRIOS 3® to maximize the accuracy of the device's scanning by performing a digital scan under LS (1.003 lux). The illuminations tested by Wesemann *et al.* (2021) did not influence the AC scans with 3Shape TRIOS®. Therefore, accuracy can be improved with appropriate lighting in AC. In contrast, in the *in vitro* study by Ochoa-López *et al.* (2022),[10] 3Shape TRIOS® obtained the highest accuracy (34.0 ± 3.3 μm) and precision (24.5 ± 14.9 μm) under 100 lux in digital AC scans with the presence of an implant, obtained with different IOS. It is observed that, when it comes to AC, the precision findings of this study regarding the IOS 3Shape TRIOS under LC (10,000 lux) and LS (1,003 lux), even when using millimeter measurements, are consistent with the results of Revilla-León *et al.* (2020a, c, 2021),[28,30,32] who used micrometer measurements. It is worth noting that the evaluated IOS in this study and others, under the tested lighting conditions, presented accuracy and precision values below the acceptable limit of 100 μm for AC scans.

The ambient lighting types used, with their respective acronyms (LC, LS, LN, and SL), aim to facilitate reader comprehension, as they follow the European Lighting Standards (prEN 12464-1) (ECS, 2022). According to some authors,[10,28-31] the fundamental factor is the quantification of illuminance in the subject's mouth, which should be controlled by the professional using a luxmeter. Therefore, professionals should consider ambient lighting conditions as a critical factor influencing the accuracy of IOS and include a luxmeter in the digital device arsenal.[31]

The limitation of this study lies in the conditions of an *in vitro* research. The mandibular dental arch with intact acrylic teeth was simulated in the mouth of a dental mannequin that had acrylic cheeks, which in this case could restrict the light that reached the scanned area during the scanning process. According to ISO 5725-1, the precision of an intraoral scan can be affected by external factors such as intraoral humidity, dental preparation, and the limited space that the oral cavity allows for camera maneuvering (ISO, 2022).[20] Additionally, the scanning times with the three IOS under different tested illuminations were not evaluated. Therefore, additional *in vivo* studies are recommended to better understand the impact of lighting conditions on the accuracy of available intraoral digital scanning systems. It is also important to determine the influence of illuminance in clinical conditions and on multiple scanning substrates in full arches, while comparing different model measurement methodologies.

CONCLUSION

The obtained models showed excellent accuracy in relation to the utilized IOS, regardless of the tested lighting conditions.

The 3Shape TRIOS® IOS presented the best precision among the devices, specifically when the lighting was from the chair/reflector (LC, 10,000 lux) and room light (LS, 1,003 lux).

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