J Prosthodont Res. 2024; 68(1): 172–180

OPEN ACCESS JPR Prosthodontic Research

Journal of Prosthodontic Research

Original article

Accuracy of intraoral optical scan versus stereophotogrammetry for complete-arch digital implant impression: An *in vitro* study

Alessandro Pozzi [a,b], Enrico Agliardi [c], Fabrizio Lio [d], Katalin Nagy [e], Alessandra Nardi [f], Lorenzo Arcuri [g,*]

[a] Goldstein Center for Esthetic and Implant Dentistry, Department of Restorative Sciences, Augusta University, Augusta, USA, [b] Department of Clinical Sciences and Translational Medicine, School of Dentistry, University of Tor Vergata, Rome, Italy, [c] Dentistry Department, Vita e Salute San Raffaele University, Milan, Italy, [d] Department of Chemical Science and Technologies, Materials for Health, Environment and Energy - Dentistry, University of Tor Vergata, Rome, Italy, [e] Department of Oral Surgery, University of Szeged, Szeged, Hungary, [f] Department of Mathematics, University of Rome Tor Vergata, Rome, Italy, [g] Department of Odontostomatological and Maxillofacial Sciences, Sapienza University, Rome, Italy

Abstract

Purpose: To assess and compare the accuracies of intraoral scanners (IOS) and stereophotogrammetry (SPG) devices for complete-arch digital implant impressions.

Methods: A 4-analog model was digitized using a desk scanner to obtain a reference file. Thirty test scans were conducted using the investigated IOS device, while an additional 30 scans were performed using the SPG device. Using the best-fit algorithm, the resulting 60 test files were aligned with the reference file. Linear (ΔX, ΔY, and ΔZ-axis) and angular deviations (ΔANGLE) were evaluated. Three-dimensional (3D) deviation was calculated based on the Euclidean distance (ΔEUC). The analysis was stratified according to the scanning device and implant position. Fisher's F and t-tests were used to compare the variances and expected values of the two scanning systems.

Results: IOS expressed a higher 3D (ΔEUC) mean deviation than SPG (52.8 µm vs. 33.4 µm, $P < 0.0001$), with extreme measurements up to 181.9 µm. A significantly higher standard deviation (SD) was associated with IOS (37.1 µm vs. 17.7 µm, $P < 0.0001$). Considering angular deviations, the IOS showed slightly higher angular mean deviations (ΔANGLE) than the SPG (0.28° vs. 0.24°, $P = 0.0022$), with extreme measurements of up to 0.73°. The SPG SD values were significantly lower than the IOS SD values (0.14° vs. 0.04°, $P < 0.0001$).

Conclusions: The SPG showed significantly higher 3D and angular accuracies for complete arch implant impressions, with consistent repeatability. IOS scanning revealed significantly higher extreme deviations exceeding the acceptable threshold value. Despite study limitations, SPG appears more feasible than IOS for complete-arch digital implant impressions.

Keywords: Intraoral scanner, Stereophotogrammetry, Complete arch, Digital impression

Received 2 October 2022, Accepted 19 July 2023, Available online 11 August 2023

1. Introduction

Digital impressions are considered a valid alternative to conventional impressions for recording the intraoral anatomy and implant positions[1,2]. Since the introduction of the first digital intraoral scanner (IOS) in the 1980s, several devices based on different optical technologies, such as confocal microscopy, optical coherence tomography, active and passive stereovision and triangulation, interferometry, and phase shift principles, have been proposed[3]. Initially, the use of a coating powder was necessary to allow proper surface scanning, minimize noise, and increase the practicality[3]. Currently, the improvement of intraoral optical surface scanning technology has broadened the clinical use of digital impression techniques, which are becoming essential in modern dentistry. The IOS allows for increased operative comfort, particularly in patients with a pronounced gag reflex, and transfers the patient dataset to all dental team members, enhancing the comprehensive diagnosis, treatment plan, and patient monitoring over the years. Moreover, digital impressions eliminate errors related to impressions, pouring materials, and casting laboratory procedures[4].

Furthermore, digital impressions enhance computer-aided design and computer-aided manufacturing (CAD-CAM) production processes that enable the use of esthetic milling materials, such as zirconia and alumina, and the use of three-dimensional (3D) printing materials that cannot be cast or produced in an analogical conventional manner[4].

The IOS accuracy is reliable for digital impressions of single crowns and short-span fixed dental prostheses[5]. However, IOS accuracy is influenced by different operators (scanning technology and system selection, scanning head size, calibration, scanning distance, exposure of the IOS to ambient temperature changes, ambient humidity, ambient lighting conditions, operator experience, scanning

DOI: https://doi.org/10.2186/jpr.JPR_D_22_00251
***Corresponding author:** Lorenzo Arcuri, Department of Odontostomatological and Maxillofacial Sciences, Sapienza University, 00161 Rome, Italy.
E-mail address: lorenzo.arcuri@uniroma1.it

pattern, extension of the scan, cutting off, rescanning, and overlapping) and patient factors (tooth type, presence of interdental spaces, arch width variations, palate characteristics, wetness, existing restorations, characteristics of the surface being digitized, edentulous areas, inter-implant distance, position, angulation, depth of existing implants, and implant scanbody (ISB) selection)[6,7]. Accuracy is defined by trueness and precision (ISO5725-1). Trueness describes the conformity of measurements to actual values, and precision describes the conformity of multiple repeated measurements[8]. The IOS for complete arch implant impressions remains controversial by the dental community in terms of accuracy and practicality, particularly for the lower jaw[9,10]. A recent literature review on IOS accuracy and practicality showed that the longer the scan range, the larger the error, with trueness below 50 µm and between 50 and 250 µm for partial and complete arch digital impressions, respectively[6].

This issue is intrinsic to the IOS 3D reconstruction algorithm, which is based on the stitching imaging process. The 3D images consecutively acquired by the IOS device must be stitched using the IOS software algorithm during the scanning procedure, using reference stable points represented by teeth, gingiva, or other anatomical structures. Therefore, a scanning strategy featuring slow-speed buccolingual wave movement is mandatory to facilitate consecutive image acquisition and 3D reconstruction[4,11].

Long-span edentulous ridges and completely edentulous arches represent difficult clinical scenarios for IOS because of the lack of stable and easy-to-identify anatomical reference points. The use of artificial reference points such as adhesive landmarks, temporary anchorage device (TAD) screws, or splinting systems has been advocated to facilitate image acquisition and 3D anatomic scanning of edentulous patients, although their clinical application can be cumbersome[11].

Stereophotogrammetry (SPG) was first proposed by Lie and Jemt as a method for determining the misfit between implants and frameworks[12,13]. In 1999, Jemt *et al.* reported that this technology is a suitable substitute for conventional impressions of complete arches[14].

SPG is a digital impression technology that detects only implant coordinates, whereas intraoral dental and gingival anatomies cannot be detected[15]. SPG is based on an extraoral device with two cameras that simultaneously detect a specific optical landmark geometry featuring the surface of dedicated flag ISBs[16]. No stitching process is considered in the SPG technology[14]. The extraoral scan and different detection methods of implant coordinates without the stitching process algorithm suggest a potential clinical application of SPG as a digital alternative to IOS for complete arch implant impressions.

Studies comparing the *in vitro* accuracy of IOS and SPG for complete arch implant digital impressions are already available in the scientific literature, although conflicting results have been reported[10,17,18]. The paucity of current scientific evidence on the topic requires further investigations with larger sample sizes and powerful statistics to achieve a more detailed conclusion on the accuracy of these digital impression technologies. This *in vitro* study aimed to assess and compare the accuracy of IOS and SPG for complete arch implant impressions in a mandibular model fitted with four implant analogs. The null hypothesis was that there would be no significant differences in 3D and angular deviations between the investigated complete-arch digital implant impression techniques.

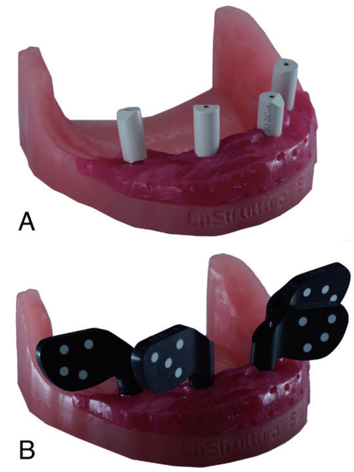

Fig. 1. A. Mandibular polymethylmethacrylate (PMMA) model with removable soft tissue frame and polyether ether ketone (PEEK) ISBs screwed onto the MUA implant analogs. B. Mandibular PMMA model with removable soft tissue frame and 4 stereophotogrammetry scanbodies screwed onto the MUA implant analogs.

2. Materials and Methods

2.1. Master model

An edentulous mandibular polymethylmethacrylate (PMMA) milled model with four multiunit implant analogs (MUA analogs; Nobel Biocare, Kloten, Switzerland) positioned at 3.2, 3.5, 4.2 and 4.5 was produced. The following implant position criteria were adopted: 3.2 (depth -1 mm, distal angulation 5°), 3.5 (depth -3 mm, mesial angulation 10°), 4.2 (depth 0 mm, angulation 0°), and 4.5 (depth -4 mm, distal angulation 15°). A removable soft tissue frame was 3D printed (NextDent 5100, 3DSystems, Rock Hill, SC, USA) with a dedicated material (Gingiva Mask, NextDent, 3DSystems, Rock Hill, SC, USA) to ensure the fit of the scan bodies on the model and to provide the opportunity to check the fit.

2.2. Reference scan

A four-Blue LED 5 MPa camera, scanner (D2000, 3 shape, Copenhagen, Denmark), properly calibrated before scanning, was used to obtain a standard tesselation language (STL) file to be used as reference. The scanner is certified for an accuracy of 5 µm, as specified in the ISO 12836 certification.

2.3. IOS and SPG scan procedures

One experienced operator who used both scanning devices and blinded to the study aims, was enrolled. A second operator secured the polyether ether ketone (PEEK) ISBs onto the MUA implant analogs with a 10 Ncm torque controlled by a dynamometer, and visually checked the proper ISB seating over the analog heads with magnifying loupes (Eyezoom 5X, Orascoptic, Middleton, WI, USA) (**Fig. 1A**). Thereafter, the second operator screwed the SPG scan bodies onto the MUA implant analogs using the same procedure (**Fig. 1B**). A total of 60 complete arch scans (30 scans for each device) were performed.

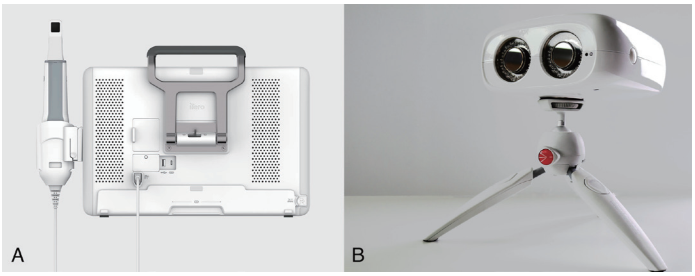

Fig. 2. A. Intraoral scanner device. B. Stereophotogrammetry device.

2.3.1. IOS scan procedure

The investigated IOS device was a pen grip (iTero Element 5D; Align Technology, Tempe, AZ, USA) (**Fig. 2A**). It is a powder-free scanner based on parallel confocal imaging laser technology. The IOS scans were acquired with a rest time of at least 5 min between the scans. The scan starting point was always the ISB at position 4.5, while 3.5 was the last one to be scanned. Before starting the investigation, the IOS calibration was performed by the producer.

The scan strategy was consistent for all scanning procedures according to the manufacturer's guidelines. The starting point for occlusal-lingual surface of the ISB was position 4.5, then it moved toward ISB 3.5, always including two surfaces, and returned from the buccal side[19].

2.3.2. SPG scan procedure

A SPG system (Precise Implant Capture, PiC camera, PiC Dental, Madrid, Spain) was used to record the implant positions (**Fig. 2B**). SPG ISBs were screwed onto multiunit abutments and their specific SPG codes were reported in the software for each implant site. The SPG camera was positioned 15–30 cm from the model at a 45° angulation. The images captured by the SPG device were processed using the SPG software to obtain the 3D coordinates of each implant in a vector format. Subsequently, STL files were exported.

2.4. Data processing and accuracy assessment

The 60 test STL files were aligned to the reference scan with dedicated software (Geomagic Studio 12, 3DSystems, Rock Hill, SC, USA) according to a 0.01 mm alignment tolerance, and two alignment optimizations were accomplished after file superimposition. Superimposition between the test and control group scans and the reference scan was obtained using the best-fit method, considering only the alignment of the implant positions and simulating a standard clinical and laboratory workflow.

The best-fit algorithm was used to measure the deviation of each implant from its analog in the reference file. Therefore, it was possible to properly analyze the 3D linear and angular deviations of each implant by considering the error distribution in the three spatial coordinates. Finally, the linear (ΔX, ΔY, and ΔZ) and angular discrepancies (ΔANGLE) between each test scan and the reference scan were measured for any analog, and the superimposed files were analyzed using dedicated measurement software (Hyper Cad S, Cam HyperMill, Open Mind Technologies, Milano, Italy) after reconstruction of the linear geometries of the analogs. The centers of the digital-analog heads were used for deviation measurements. Negative values on the X-, Y-, and Z-axes indicated an ISB positioned to the left, downward, and backward, respectively, whereas positive values were in the opposite direction on each axis. 3D deviations were calculated considering the Euclidean distance between the centers of the heads of the test and control implant analogs (ΔEUC) (**Figs. 3 and 4**)[9,11].

2.5. Statistical analysis

Assuming Euclidean distance as the primary endpoint and a significance level of 0.05, a sample size of 240 implants guaranteed a minimum expected difference of 20 μm and a test power of 0.95.

However, the sample size calculation was performed assuming an expected standard deviation of 40 μm for both IOS and SPG. Although this assumption was consistent with the observed standard deviation of the IOS, the observed SPG variability was significantly lower. Therefore, a post-hoc analysis based on the observed values was performed; assuming a test size of 0.05, the test power was 0.98.

Continuous variables are summarized as mean, standard deviation, and minimum and maximum values. Kernel density estimates were used to describe the empirical distributions. Fisher's F and t-tests were used to compare the variances and expected values between the two groups, respectively. Welch's t-test was used in cases with significantly different variances.

3. Results

Deviations between the reference scan and 60 test scans (30 IOS; 30 SPG) were calculated for each implant analog (n = 240) over the X-, Y-, and Z-axes and angulation. From the linear discrepancies, the 3D deviation was calculated in terms of the Euclidean distance (ΔEUC). The 3D and angular deviations did not consider the direction of the error. **Table 1** describes the deviations from the reference scans of the IOS and SPG.

IOS expressed higher 3D mean deviations (ΔEUC) compared to SPG (52.8 μm vs. 33.4 μm $P < 0.0001$) with extreme measurements up to 181.9 μm. Moreover, a significantly higher standard deviation (SD) was associated with IOS (37.1 μm vs. 17.7 μm $P < 0.0001$).

Considering angular deviations (ΔANGLE), IOS showed slightly higher mean deviations than SPG (0.28° vs. 0.24°, $P = 0.0022$), with extreme measurements of up to 0.73°. The SPG SD values were significantly lower than the IOS SD values (0.14 vs. 0.04°, $P < 0.0001$).

Tables 2 and 3 present the 3D and angular discrepancies stratified according to implant position and scanning device. The corresponding empirical distributions are shown in **Figures 5 and 6**.

Considering ΔEUC, implant site 4.5 was the most critical position to be scanned with the IOS (deviations up to 181.88 μm), while the anterior implants (4.2 and 3.2) were more critical for scanning with the SPG. The 3D variability was significantly reduced for SPG compared to IOS for all implants, except for implant 4.2, where the reduction in variability did not reach significance. No significant mean difference was observed between the two devices for implant 4.2 as well.

Figure 5 shows how IOS and SPG performed similarly for anterior implant 4.2; for posterior implants (4.5, 3.5), an evidently better

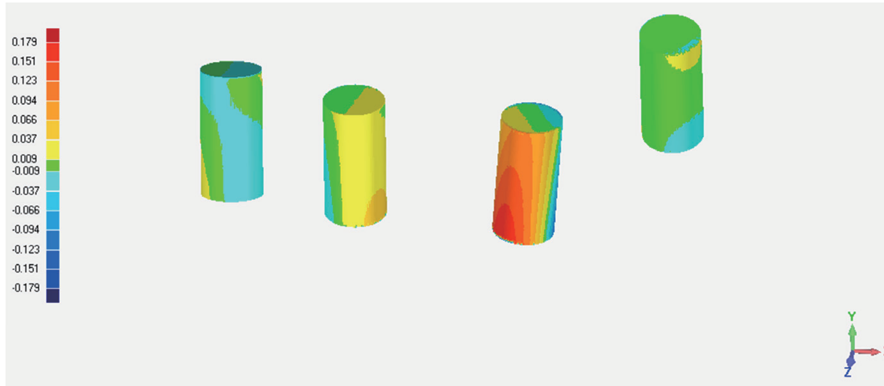

Fig. 3. Best fit algorithm alignment to superimpose the 4 implant positions of the test files with the corresponding positions of the reference file

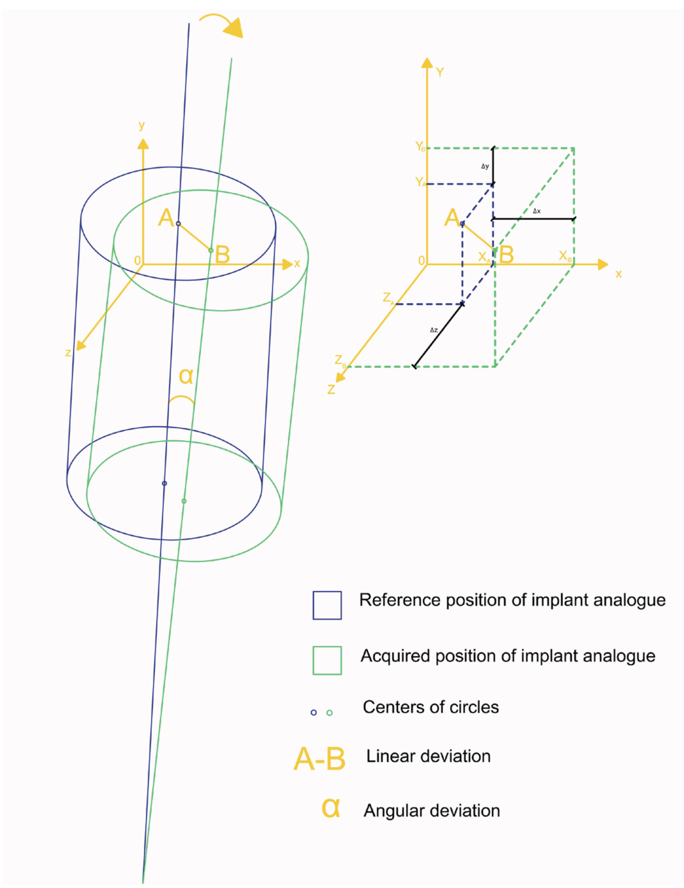

Fig. 4. 3D and angular deviation assessment. The 3D linear deviation (ΔEUC) was calculated as the distance between the head centers of the reference (A) and the corresponding reference of the acquired analog position (B). That distance was decomposed into the 3 space axes to calculate linear deviations (ΔX, ΔY, ΔZ). The angular deviation was calculated as the angle formed by the two lines passing orthogonally to the head of the analogs through Points A and B.

performance of SPG was detected, especially for implant 4.5.

Considering ΔANGLE, no significant differences were found in terms of implant position. The expected angular discrepancy was significantly different between the IOS and SPG only for implant 4.2 (0.40° vs. 0.23°, $P < 0.0001$). However, SPG always performed significantly better than IOS in terms of SD.

4. Discussion

This *in vitro* study analyzed and compared the accuracy of two digital impression methods (IOS and SPG) for complete arch implant impressions. The trueness and precision of IOS and SPG were compared as linear and angular deviations, respectively. The null hypothesis was rejected because the SPG performed better than the IOS in terms of both 3D (ΔEUC) trueness ($P < 0.0001$) and precision ($P < 0.0001$). Considering angular deviations (ΔANGLE), the SPG performed better than the IOS in terms of angular trueness ($P = 0.0022$) and precision ($P < 0.0001$). IOS expressed higher 3D mean deviations (ΔEUC) compared to SPG (52.8 µm vs. 33.4 µm $P < 0.0001$) with extreme measurements of up to 181.9 µm. A significantly higher SD was associated with IOS (37.1 µm vs. 17.7 µm $P < 0.0001$). Considering angular deviations (ΔANGLE), IOS showed slightly higher mean deviations than SPG (0.28° vs. 0.24°, $P = 0.0022$), with extreme measurements of up to 0.73°. The SPG SD values were significantly lower than the IOS SD values (0.14° vs. 0.04°, $P < 0.0001$).

The study design was based on the use of a best-fit alignment between the reference and test scans to measure the deviations for each implant position and further analyze the 3D deviation in each of the three space axes. The best-fit algorithm allows the deviation measurement of all implant positions by comparing the respective test and reference files. Thus, it was possible to properly analyze the deviations of each implant from a linear (ΔY, ΔX, ΔZ), 3D (ΔEUC) and angular (ΔANGLE) point of view. The Euclidean distance, as an index of 3D deviation, was preferred to the root mean square (RMS), as it is easier to translate as a metric outcome in clinical practice. The choice of a certified 5 µm accuracy optical desk scanner as a reference was justified by its better access to the freedom plane compared to tactile systems, such as the coordinate measuring machine (CMM)[20].

The study's limitations include being conducted in an *in vitro* environment, which may have underestimated deviations due to patient factors, such as saliva, blood, tongue, and movements[21]. However, the SPG extraoral scan offers a potential digital alternative to the IOS for complete-arch implant impressions, as it overcomes these limitations. In vivo studies are recommended to assess SPG's accuracy and practicality of SPG in challenging complete arch cases

Table 1. Descriptive analysis intraoral scanner (IOS) and stereophotogrammetry (SPG) linear, 3D and angular deviations

	IOS			SPG		
	Mean	Std. Deviation	Range	Mean	Std. Deviation	Range
ΔY (µm)	-2.03	14.54	(-71.86, 18.77)	0.95	7.15	(-13.09, 18.42)
ΔX (µm)	5.21	50.51	(-87.29, 146.55)	12.81	19.23	(-52.86, 51.67)
ΔZ (µm)	-1.85	37.31	(-117.53, 82.95)	20.78	20.42	(-43.16, 75.97)
ΔEUC (µm)	52.81	37.11	(4.18, 181.88)	33.42	17.71	(7.56, 80.34)
ΔANGLE (°)	0.28	0.14	(0.03, 0.73)	0.24	0.04	(0.15, 0.36)

Table 2. 3D distances (ΔEUC) stratified by implant and scanning device (µm). The F and t-tests were used to compare the variances and expected values between the two groups (intraoral scanner [IOS] and stereophotogrammetry [SPG]).

	IOS			SPG				
Implant	Mean	Std. Deviation	Range	Mean	Std. Deviation	Range	F test *P*-value	T test *P*-value
4.5	81.85	48.22	(15.72, 181.88)	29.25	3.73	(17.57, 35.41)	<0.0001	<0.0001*
4.2	43.46	22.43	(10.82, 81.59)	48.58	19.37	(15.36, 80.34)	0.4350	0.3474
3.2	56.14	27.17	(5.07, 103.18)	41.06	14.41	(22.54, 77.18)	0.0010	0.0102*
3.5	29.79	23.73	(4.18, 107.22)	14.78	3.83	(7.56, 22.51)	<0.0001	0.0018*

* *P*-value refers to Welch's t-test

Table 3. Angular discrepancies (ΔANGLE) stratified by implant and scanning device (°). The F-test and T test were used to compare the variances and expected values between the two groups (intraoral scanner [IOS] and stereophotogrammetry [SPG]).

	IOS			SPG				
Implant	Mean	Std. Deviation	Range	Mean	Std. Deviation	Range	F test *P*-value	T test *P*-value
4.5	0.29	0.13	(0.08, 0.73)	0.29	0.05	(0.19, 0.36)	<0.0001	0.8719*
4.2	0.40	0.13	(0.15, 0.67)	0.23	0.02	(0.20, 0.27)	<0.0001	<0.0001*
3.2	0.21	0.11	(0.03, 0.41)	0.24	0.02	(0.20, 0.29)	<0.0001	0.1820*
3.5	0.24	0.12	(0.09, 0.52)	0.21	0.03	(0.15, 0.26)	<0.0001	0.1728*

* *P*-value refers to Welch's t-test

with varying levels of bone and soft-tissue atrophy. The findings of this study are specific to the investigated IOS and SPG systems, and should be cautiously applied to other devices. While the scans were performed by a single expert clinician, previous research indicated no significant operator effect on the IOS accuracy[9]. Further research should explore the operator effect and learning curve of the SPG technology, as this information is currently lacking in the literature.

The study results were in line with the findings of a recent *in vitro* study by Thome *et al.*, who measured and compared the scan body coordinates of the reference cast with the scan body positions obtained using the conventional (impression plaster), IOS, and SPG techniques[17]. Thome *et al.* used the same SPG device as in the present study and a desk scanner with an accuracy of 7 µm as a reference. Moreover, the study analyzed the global angular distortion and 3D deviations of the entire scan body and flat-angled surface using an inspection and metrology software program and the best-fit alignment technique. Although the methods and IOS were different compared to those in the present study, the SPG technique reported the highest accuracy in terms of trueness and precision for the intraoral scan bodies of all the techniques evaluated.

Another *in vitro* study compared the accuracy of a conventional technique (elastomeric impression), SPG, and two IOSs using a CMM with a nominal linear accuracy of 1 µm as a reference and showed completely different results[10]. The SPG system (iCam4D; Imetric4D Imaging Sàrl, Courgenay, Switzerland) provided the least accurate values with the highest 3D discrepancy for implant positions among all groups, with a mean 3D deviation of 77.6 µm.

Another study compared the accuracy of conventional techniques (polyether impression) and SPG and IOS for complete-arch implant impressions using a 4 µm accuracy laboratory scanner as a reference[18]. The test and control files were superimposed using a best-fit algorithm, and the 3D discrepancy between the two STL files was evaluated using the RMS error calculated by the inspection software. The SPG obtained the lowest 3D discrepancy in terms of trueness and precision for the implant abutment positions, whereas the IOS showed the least accuracy among the three impression techniques tested. The two aforementioned studies investigated the same SPG system (iCam4D; Imetric4D Imaging Sàrl, Courgenay, Switzerland), although different reference systems (desk scanner) and analyzed measurements (RMS) were used. These differences in study designs justify the contradictory results reported. The authors reported a dramatically low mean 3D deviation of 33.4 ± 17.7 µm of the investigated SPG system (Precise Implant Capture, PiC camera, PiC dental, Madrid, Spain).

In the present study, IOS showed higher 3D mean deviations than SPG (52.8 µm vs. 33.4 µm $P < 0.0001$), with extreme measure-

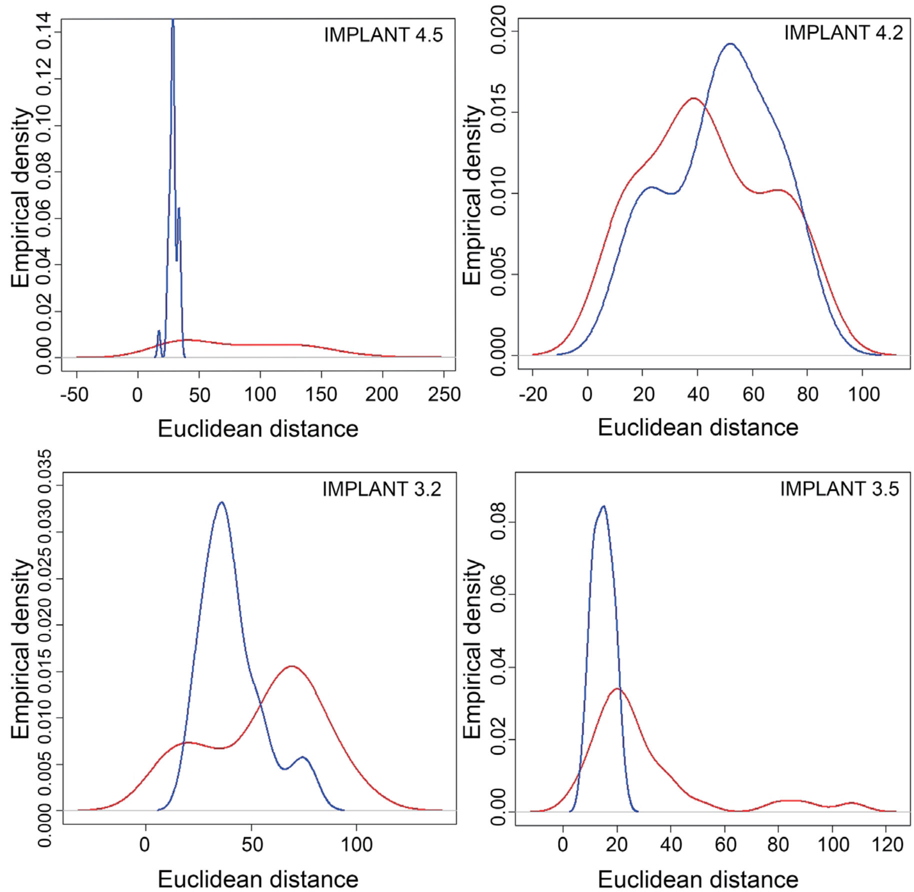

Fig. 5. Empirical distributions of 3D distances (ΔEUC) stratified for implant and scanning device (red= intraoral scanner, blue= stereophotogrammetry)

ments of up to 181.9 μm. Analyzing the 3D deviation into the three space axes, IOS expressed higher deviations on the X-axis (lateral) of 5.21 ± 50.51 μm, while SPG expressed a very high accuracy on the Y-axis (vertical) of 0.95 ±7.15 μm. The extreme IOS deviation values observed in the present study were above the clinically acceptable misfit of 150 μm, which is recommended to prevent long-term mechanical and biological complications[22–24]

Concerning angular deviations, the IOS showed slightly higher mean deviations than the SPG (0.28° vs. 0.24°, P = 0.0022), with extreme measurements up to 0.732°.

The reported IOS angular deviations may negatively affect the overall implant-prosthesis fit, particularly in the case of screw-retained complete-arch restorations.

Considering the 3D deviations stratified per implant position, implant 4.5 was the most critical position to be scanned, with IOS deviations up to 181.87 μm, while anterior implants 4.2 and 3.2 were more critical to be scanned for the SPG (deviations up to 80.34 and 77.18 μm).

The intrinsic limitations of the optical surface scanning technology require a consistent and flawless scanning route to reduce the number of images and stitching procedures. Therefore, as advised by the manufacturer of the investigated IOS, the scan should start from the most distal implant and proceed along the dental arch from left to right or right to left.

To facilitate further comparisons, we adopted a previously published scanning strategy[9,19]. The starting point for scanning was the occlusal-lingual surface of the ISB at position 4.5. The scan then moved along the arch toward positions 4.2, 3.2, and 3.5. The scanning process was then reversed, starting from the occlusal-buccal side. Although the IOS starting point usually features better trueness and accuracy, in the present study, position 4.5 was critical because it was characterized as the most challenging position in terms of depth and angulation (depth, -4 mm; distal angulation, 15°), in agreement with previous reports[2].

For all implants except 4.2, the SPG device demonstrated a significant reduction in 3D variability compared to the IOS device. No significant differences were observed between the two devices for implant 4.2. These results confirmed the higher accuracy of SPG, even though a slight reduction in accuracy was noted for the anterior implants for both trueness and precision. This reduction in accuracy for the anterior implant positions led to a similar or higher level of accuracy compared with the IOS. The authors assumed that the worse SPG performance in the anterior implants than in the posterior implants may be related to the scanning mode of the investigated

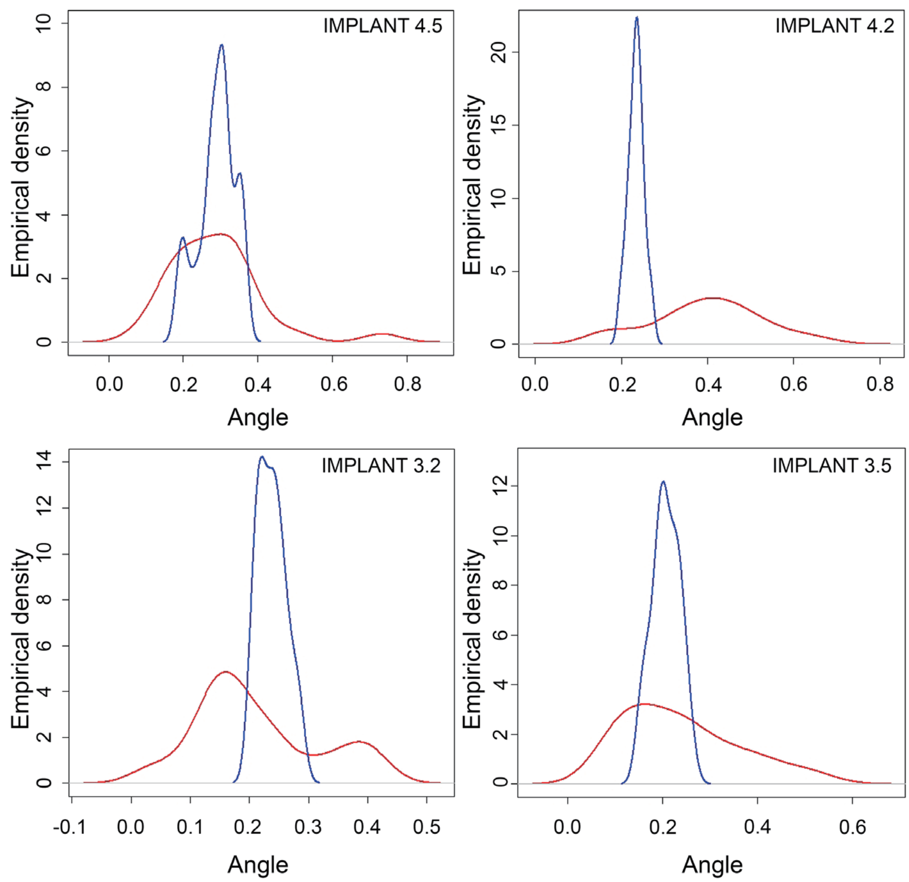

Fig. 6. Empirical distributions of angular discrepancies (ΔANGLE) stratified by implant and scanning device (red= intraoral scanner, blue= stereophotogrammetry)

model. The model being secured on a table prompted the operator to position the SPG device at a 45° angle relative to the dedicated ISB flags. This may explain the worse accuracy recorded for the anterior positions by the SPG compared with the posterior positions. The SPG scanning orientation recommended by the manufacturer should be as close as possible to the dedicated ISB flags screwed onto the implants.

Considering ΔANGLE, no significant difference was found in terms of implant position. The expected angular discrepancy was significantly different between the IOS and SPG only for implant 4.2 (0.40° vs. 0.23°, $P < 0.0001$). However, SPG always performed significantly better than IOS in terms of the SD. Therefore, despite the *in vitro* environment that may have facilitated IOS surface scanning, SPG showed a higher accuracy in both 3D and angular measurements. This is probably because of the different technologies of the two devices. The IOS software elaborates and matches the acquired 3D images through a process known as "stitching," based on a best-fit algorithm. This process was repeated for each image matching and was responsible for the stitching-related deviation for each image coupling. The higher the number of image stitches, the higher the overall error associated with the best-fit alignment[4]. SPG is based on an extraoral device with two infrared charge-coupled device cameras that simultaneously detect a specific optical landmark geometry featuring the surface of each flag ISB, thereby recording the implant coordinates and their spatial relationship in terms of distances and angulations[16]. Because of the larger field of view compared to the currently available IOS devices, SPG simultaneously detects all the implant coordinates and their space relationships with no stitching procedure needed, and is not subject to this type of error source.

Furthermore, SPG, owing to its extraoral scanning approach, is not influenced by any of the intraoral factors reported in the literature, such as the patient's mouth opening, size of the scanner tip, saliva, steam, manufacturing material of the scan bodies, distance between them, and length of the edentulous span and arch. Finally, SPG infrared technology is not affected by ambient light or light reflection[25].

Furthermore, a significantly higher SD was associated with IOS both in terms of 3D deviation (37.1 µm vs. 17.7 µm $P < 0.0001$) and angular deviation (0.14° vs. 0.04° $P < 0.0001$).

According to the SD data for the 3D and angular deviations, the SPG showed much higher precision than the IOS. This evidence demonstrates the dramatically higher recording repeatability of the SPG, which could be explained by the different procedures of the two digital impression devices. The IOS should be adequately moved by the clinician along the arch according to a proper scanning strategy to record all ISB positions and the surrounding gingival anatomy, thus allowing fast and accurate stitching of the acquired 3D images. SPG is an extraoral digital device that does not need to be moved along the arch but only requires small movements to correctly focus the SPG scan body geometry[26]. Hence, the operator influence is more evident in the use of the IOS and could lead to lower consistency in the measurement procedures. It must be specified that the SPG, as an extraoral scanning device, can detect only the implant positions without recording the surrounding gingival anatomy. For this reason, a second intraoral impression, by means of an IOS or a traditional technique to be digitized later, is necessary to supply the dental technician with a master model that includes all the anatomical information of the edentulous jaw. Moreover, few SPG devices are currently available in the global market, and their cost is higher than that of IOS systems.

To summarize the study findings and their clinical implications:

- The SPG performed better than the IOS in terms of both linear and angular trueness and precision.
- Extreme IOS linear and angular deviations were above the clinically acceptable misfit and may negatively affect the overall implant-prosthesis joint, particularly in screw-retained complete arch restorations.
- The SPG extraoral digital impression is not influenced by any intraoral patient factors, and its infrared technology is not affected by ambient light or light reflection.
- The SPG has a larger field of view than the IOS and simultaneously detects all implant coordinates and their spatial relationship with no stitching procedures.
- Stereophotogrammetry seems to be more feasible for complete arch digital implant impressions than IOS, even though it can only detect implant positions and must be integrated with IOS to record the surrounding gingival anatomy.

5. Conclusions

The SPG complete-arch implant impression showed significantly higher 3D and angular accuracies than the IOS. The SPG showed consistent performance in terms of measurement repeatability. The extreme deviations reported by the IOS were far above the clinically acceptable threshold value, despite the *in vitro* environment that may have facilitated optical surface scanning. Considering the limitations of the current study, stereophotogrammetry appears to be more feasible than IOS for complete arch digital implant impressions. The reported IOS deviations may negatively affect the overall implant-prosthesis fit, particularly in screw-retained complete-arch restorations. Further randomized clinical trials are necessary to investigate the clinical performance of this technology *in vivo*.

Acknowledgments

We wish to thank LaStruttura Spa for the model production and Dr. Andrea Papa for expertise in 3D metrology. We thank the MIUR Excellence Department Project awarded to the Department of Mathematics at the University of Rome, Tor Vergata.

Conflict of interest statement

All the authors declare no potential conflicts of interest in the present scientific paper.

References

[1] Amin S, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Digital vs. conventional full-arch implant impressions: a comparative study. Clin Oral Implants Res. 2017;28:1360–7. https://doi.org/10.1111/clr.12994, PMID:28039903

[2] Rutkūnas V, Gečiauskaitė A, Jegelevičius D, Vaitiekūnas M. Accuracy of digital implant impressions with intraoral scanners. A systematic review. Eur J Oral Implantology. 2017;10(suppl 1):101–20. PMID:28944372

[3] Logozzo S, Zanetti EM, Franceschini G, Kilpelä A, Mäkynen A. Recent advances in dental optics – Part I: 3D intraoral scanners for restorative dentistry. Opt Lasers Eng. 2014;54:203–21. https://doi.org/10.1016/j.optlaseng.2013.07.017

[4] Kihara H, Hatakeyama W, Komine F, Takafuji K, Takahashi T, Yokota J, *et al.* Accuracy and practicality of intraoral scanner in dentistry: A literature review. J Prosthodont Res. 2020;64:109–13. https://doi.org/10.1016/j.jpor.2019.07.010, PMID:31474576

[5] Imburgia M, Logozzo S, Hauschild U, Veronesi G, Mangano C, Mangano FG. Accuracy of four intraoral scanners in oral implantology: a comparative in vitro study. BMC Oral Health. 2017;17:92. https://doi.org/10.1186/s12903-017-0383-4, PMID:28577366

[6] Revilla-León M, Kois DE, Kois JC. A guide for maximizing the accuracy of intraoral digital scans. Part 1: operator factors. J Esthet Restor Dent. 2023;35:230–40. https://doi.org/10.1111/jerd.12985, PMID:36479807

[7] Revilla-León M, Kois DE, Kois JC. A guide for maximizing the accuracy of intraoral digital scans: Part 2—Patient factors. J Esthet Restor Dent. 2023;35:241–9. https://doi.org/10.1111/jerd.12993, PMID:36639916

[8] Flügge T, Att W, Metzger M, Nelson K. Precision of dental implant digitization using intraoral scanners. Int J Prosthodont. 2016;29:277–83. https://doi.org/10.11607/ijp.4417, PMID:27148990

[9] Arcuri L, Pozzi A, Lio F, Rompen E, Zechner W, Nardi A. Influence of implant scanbody material, position and operator on the accuracy of digital impression for complete-arch: A randomized in vitro trial. J Prosthodont Res. 2020;64:128–36. https://doi.org/10.1016/j.jpor.2019.06.001, PMID:31255546

[10] Revilla-León M, Att W, Özcan M, Rubenstein J. Comparison of conventional, photogrammetry, and intraoral scanning accuracy of complete-arch implant impression procedures evaluated with a coordinate measuring machine. J Prosthet Dent. 2021;125:470–8. https://doi.org/10.1016/j.prosdent.2020.03.005, PMID:32386912

[11] Pozzi A, Arcuri L, Lio F, Papa A, Nardi A, Londono J. Accuracy of complete-arch digital implant impression with or without scanbody splinting: an in vitro study. J Dent. 2022;119:104072. https://doi.org/10.1016/j.jdent.2022.104072, PMID:35189313

[12] Lie A, Jemt T. Photogrammetric measurements of implant positions. Description of a technique to determine the fit between implants and superstructures. Clin Oral Implants Res. 1994;5:30–6. https://doi.org/10.1034/j.1600-0501.1994.050104.x, PMID:8038342

[13] Jemt T, Lie A. Accuracy of implant-supported prostheses in the edentulous jaw. Analysis of precision of fit between cast gold-alloy frameworks and master casts by means of a three-dimensional photogrammetric technique. Clin Oral Implants Res. 1995;6:172–80. https://doi.org/10.1034/j.1600-0501.1995.060306.x, PMID:7578793

[14] Jemt T, Bäck T, Petersson A. Photogrammetry--an alternative to conventional impressions in implant dentistry? A clinical pilot study. Int J Prosthodont. 1999;12:363–8. PMID:10635208

[15] Agustín-Panadero R, Peñarrocha-Oltra D, Gomar-Vercher S, Peñarrocha-Diago M. Stereophotogrammetry for recording the position of multiple implants: Technical description. Int J Prosthodont. 2015;28:631–6. https://doi.org/10.11607/ijp.4146, PMID:26523726

[16] Gómez-Polo M, Gómez-Polo C, del Río J, Ortega R. Stereophotogrammetric impression making for polyoxymethylene, milled immediate partial fixed dental prostheses. J Prosthet Dent. 2018;119:506–10. https://doi.org/10.1016/j.prosdent.2017.04.029, PMID:28709673

[17] Tohme H, Lawand G, Chmielewska M, Makhzoume J. Comparison between stereophotogrammetric, digital, and conventional impression techniques in implant-supported fixed complete arch prostheses: An in vitro study. J Prosthet Dent 2021;S0022-3913(21)00269-9.

[18] Ma B, Yue X, Sun Y, Peng L, Geng W. Accuracy of photogrammetry, intraoral scanning, and conventional impression techniques for complete-arch implant rehabilitation: an in vitro comparative study. BMC Oral Health. 2021;21:636. https://doi.org/10.1186/s12903-021-02005-0, PMID:34893053

[19] Müller P, Ender A, Joda T, Katsoulis J. Impact of digital intraoral scan strategies on the impression accuracy using the TRIOS Pod scanner. Quintessence Int. 2016;47:343–9. https://doi.org/10.3290/j.qi.a35524, PMID:26824085

[20] Mizumoto RM, Yilmaz B, McGlumphy EA Jr, Seidt J, Johnston WM. Accuracy of different digital scanning techniques and scan bodies for complete-arch implant-supported prostheses. J Prosthet Dent. 2020;123:96–104. https://doi.org/10.1016/j.prosdent.2019.01.003, PMID:31040026

[21] Rutkunas V, Gedrimiene A, Akulauskas M, Fehmer V, Sailer I, Jegelevicius D. In vitro and in vivo accuracy of full-arch digital implant impressions. Clin Oral Implants Res. 2021;32:1444–54. https://doi.org/10.1111/clr.13844, PMID:34543478

[22] Schwarz MS. Mechanical complications of dental implants. Clin Oral Implants Res. 2000;11(suppl 1):156–8. https://doi.org/10.1034/j.1600-0501.2000.011S1156.x, PMID:11168264

[23] Aglietta M, Siciliano VI, Zwahlen M, Brägger U, Pjetursson BE, Lang NP, *et al.* A systematic review of the survival and complication rates of implant supported fixed dental prostheses with cantilever extensions after an observation period of at least 5 years. Clin Oral Implants Res. 2009;20:441–51. https://doi.org/10.1111/j.1600-0501.2009.01706.x, PMID:19522975

[24] Pozzi A, Arcuri L, Fabbri G, Singer G, Londono J. Long-term survival and success of zirconia screw-retained implant-supported prostheses for up to 12 years: A retrospective multicenter study. J Prosthet Dent. 2023;129:96–108. https://doi.org/10.1016/j.prosdent.2021.04.026

[25] Peñarrocha-Diago M, Balaguer-Martí JC, Peñarrocha-Oltra D, Balaguer-Martínez JF, Peñarrocha-Diago M, Agustín-Panadero R. A combined digital and stereophotogrammetric technique for rehabilitation with immediate loading of complete-arch, implant-supported prostheses: A randomized controlled pilot clinical trial. J Prosthet Dent. 2017;118:596–603. https://doi.org/10.1016/j.prosdent.2016.12.015, PMID:28385445

[26] Pradíes G, Ferreiroa A, Özcan M, Giménez B, Martínez-Rus F. Using stereophotogrammetric technology for obtaining intraoral digital impressions of implants. J Am Dent Assoc. 2014;145:338–44. https://doi.org/10.14219/jada.2013.45, PMID:24686966