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CLINICAL RESEARCH

Accuracy of a smartphone app and photogrammetry algorithm in complete arch digital implant capture: An in vivo comparative study

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ABSTRACT

Statement of problem. A photogrammetry algorithm integrated into a smartphone application has been proposed as an alternative to photogrammetry scanners for complete arch digital implant recording. Clinical studies, however, are lacking.

Purpose. The purpose of this clinical study was to evaluate the accuracy of a photogrammetry app for complete arch prostheses supported by 6 implants.

Material and methods. A total of 8 participants with 10 completely edentulous arches with 6 multiunit implant abutments were recruited. For each participant, 5 recordings were made using a photogrammetry app (PIC app; Pic dental), and 1 recording with a photogrammetry device (PIC system; PIC dental). From the resulting standard tessellation language (STL) files, linear and angular Euclidean distances were recorded. A statistical analysis of the measurements obtained was used to determine their trueness and precision. The Shapiro–Wilk tests were run to analyse the trueness data, and the Levene test was used to assess the precision values (α=.05).

Results. The mean ±standard deviation absolute difference between the PIC system and PIC app was 21 ±16 µm and 0.20 ±0.17 degrees. The interimplant distance did not signifficantly affect linear trueness (P>.05) or angular trueness (P>.05). The arch type did affect linear trueness P<.001, but did not affect angular truness (P=.310).

Conclusions. The results suggested that the photogrammetry app was sufficiently accurate for recording implant locations in complete arch prostheses supported by 6 implant abutments. (J Prosthet Dent 2026;135:777.e1-e9)

Extraoral photogrammetry (EPG) systems have been reported to provide a reliable procedure for recording 3-dimensional (3D) implant positions in complete arch implant-supported prostheses.[1–13] Their trueness values have been reported to range from 10 to 77 µm, with precision values from 2 to 203 µm.[10,14–16]

Although they represent a consistent alternative to intraoral scanners (IOSs) for complete arch implant recording,[17–20] the widespread adoption of these methods has been constrained mainly by both the requirement of an initial investment and a second soft-tissue recording.[6,11] Consequently, intraoral photogrammetry (IPG) systems and scan body splinting methods have emerged.[10,15,21–23] IPG systems offer the advantage of using a single scanner for the registration of soft tissue information, adjacent teeth, antagonist arch, and maxillomandibular relationships. Therefore, all the information needed to design and fabricate an implant-supported prosthesis can be recorded by using the

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Clinical Implications

The PIC app enables broader accessibility to extraoral photogrammetry by leveraging smartphones. It offers an accurate and cost-efficient alternative to conventional bulky extraoral and intraoral photogrammetry systems.

same IOS system, limiting the approach to a single investment to perform all recording procedures.[24–26] However, IPG systems are based on the same premise as the IOSs. In order to align the optical markers, it is necessary to implement a best-fit algorithm with photogrammetry. The use of an IOS captor that is smaller than the scanned object results in IPG scanners having to stitch the scans by overlapping to create the 3D registration. This stitching method in IOSs has been reported to create inaccuracies in the implant positions that are distal to the start of the scan.[25,27–30]

An alternative to EPG involves connecting the scan bodies in implant capturing using IOSs. Various methods of splinting scan bodies have been suggested, including the use of calibrated and noncalibrated frameworks.[31–37] However, these methods entail additional procedures and costs and require a second recording of the implant positions. While it is not yet clear whether scan body splinting can improve the scanning accuracy, it does speed up the process given the difficulty of scanning edentulous areas that lack references, especially in the mandible.[27,38,39]

Such complications in scanning edentulous areas with mobile tissue and without anatomic landmarks, along with the stitching errors, do not appear with EPG devices. EPG eliminates the need for stitching captured images to create a standard tessellation language (STL) file such as those generated by IOS software programs.[3,40–46]

These advantages, in addition to the absence of initial investment, makes the Precise Implant Capture (PIC) app (Precise Implants Capture; PIC dental) an alternative to high-cost EPG systems or IPG scanners that use image stitching. This newly developed smartphone app uses a photogrammetry algorithm to perform real-time detection of the fiducial markers. Specific photogrammetry (PG) measurement algorithms process a series of 15 to 25 photographs to generate an STL file that contains the interrelated implant positions and angulations.[28]

The accuracy of this smartphone-based EPG device was reported in a recent in vitro study[28] that compared the trueness and precision of two EPG devices, the PIC system and PIC app, and reported mean differences of 12.70 µm and 0.07 degrees, respectively. Whether the impact of such differences would be clinically relevant requires further assessment with in vivo studies.[8,17,18,41,47,48] As defined by the International Organization for Standardization (ISO) 5725–1 standard,[49] accuracy comprises trueness and precision.

The purpose of this clinical study was to evaluate the accuracy of a newly introduced PG algorithm and smartphone app (PIC app; PIC Dental) for complete arch implant recording as compared with an EPG system (PIC system; PIC Dental). Additionally, the study aimed to investigate the potential impact of implant span—defined as the distance between dental implants—and dental arch type—referring to whether the prosthesis is positioned in the maxillary or mandibular arch—on the accuracy of both linear and angular measurements. The null hypotheses were that no statistically significant differences in trueness and precision would be found among complete arch implant recordings captured with the smartphone EPG app and the EPG system and that the interimplant distance or the dental arch type would not affect the accuracy of the recordings.

MATERIAL AND METHODS

In this controlled, nonrandomized clinical study, 8 individuals (2 women and 6 men), aged between 62 and 82 years and with 10 edentulous arches (8 maxillary and 2 mandibular) were enrolled. Six implants had been placed in each arch. A total of 60 optical recordings were made, 50 with the PIC app and 10 with the PIC system (reference). The study protocol had been approved by the Research Ethics Committee of the Jiménez-Díaz Foundation (PIC28–25_OTROS) and by the Research Ethics Committee of the European University of Madrid (2025–229). The study was conducted at the dental clinic of the European University of Madrid between April and May 2025.

The inclusion criteria were participants with a completely edentulous maxilla or mandible and with 6 osseointegrated implants and implant abutments (MultiUnit Abutment; IPD Dental Group) tightened to 30 Ncm by following the manufacturer's guidelines. Participants with limited mouth opening or fewer implants were excluded. All participants gave written consent to the study before inclusion. Recent in vivo studies on complete arch implant recording used a sample size similar to that of the present clinical study.[12,23,37]

A total of six recordings (n=6) were obtained per participant arch (n=10), including 5 using the PIC app (n=5) and 1 with the PIC system, which served as the reference.

Manufacturer's fiducial markers, PIC transfers (PIC transfer, HC MUA Metal, Ø4.8mm; PIC Dental) were

Figure 1. Precise Implant Capture (PIC) abutments screwed onto implant abutments for recording.

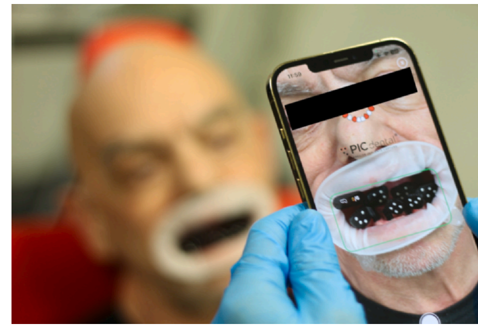


Figure 2. Clinical scenario for recording digital 3-dimensional position of specific stereophotogrammetry scan bodies with Precise Implant Capture (PIC) app.

positioned on each implant abutment at 10 Ncm of torque, according to the manufacturer's recommendations (Fig. 1). These optical markers were placed so that they were visible to the camera of both systems in each participant. Each PIC transfer was coded in each system prior to the optical recordings. The same new batch of fiducial markers with reference PT: MUA 180 was used in all participants and recordings. The fiducial markers in the most distal positions were placed toward the lingual or palatal and the rest toward the buccal. They were placed with a slight angulation to avoid reflections that could have hindered recording. All scans were conducted by a single prosthodontist (A.S.L.) with more than 10 years of experience using EPG systems under room light conditions (500 lux) measured by a light meter (LX1330B Light Meter; Dr. Meter Digital Illuminance).

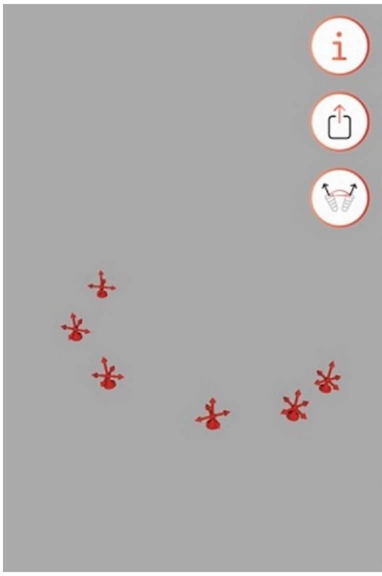
The PIC app (PIC app; PIC Dental) was a smartphone-based PG device. It detected in real time the fiducial markers using machine learning models and specific PG measurement algorithms. A smartphone (iPhone 16 Pro; Apple Inc) was used for all the implant recordings. To capture high-resolution 48 MP Fusion photographs, the camera settings of the smartphone were set to a 24 mm focal length and an aperture of ƒ1.78.

A total of 50 recordings were made with the PIC app positioned at a 20- to 30-cm scanning distance and at different angulations. The first photograph was made from a central position and from the front. Then, approximately 15 to 25 additional photographs were made for each participant, varying the inclination in both the upward and downward directions. The same procedure was repeated from the right and left lateral views of the participant. Unlike the PIC system, with this app, no implant references were needed, and not all fiducial markers needed to appear on the screen at the same time. The smartphone was advanced to locate the required scanning distance associated with the fixed focus design (Fig. 2). The photographs were made manually in sequence, with the angle between each shot varying. The PG-coded white dots on each optical marker had to be framed for the measurement to progress. On the screen, the measuring algorithm displayed progress as a percentage, and an odontogram represented the position of each implant. Implants that had not yet been captured appeared in red, implants that had been detected but required more data to complete appeared in yellow, and implants that had been completely measured appeared in green. When the recording was complete for each participant, 100% appeared in green on the screen.

As the reference recording, 1 scan was performed per participant using the PIC system (Fig. 3), positioned at a scanning distance of 20 to 30 cm and a scanning angle of 30 to 45 degrees.[50] Three PIC transfers were selected as implant reference: one in each posterior zone and one in the anterior zone of the arch.[51]

The associated software program for the PIC app (PIC app; PIC system) and the PIC system (PIC suite v1.1.48.0) calculated the linear (in micrometers) and angular (in degrees) Euclidean distances among the implant optical markers of each group[1,2,5] (Fig. 4). All the possible combinations (n=15) of interimplant linear and angular deviations were analyzed in each recording. In total, 60 STL files containing linear (n=750) and angular measurements (n=750) were obtained (Fig. 5).

Figure 3. Clinical scenario for recording digital 3-dimensional position of fiducial markers with Precise Implant Capture (PIC) system (reference).



	37	35	32	42	45	47
37	37	4,97° 9,38mm	**12,89° 36,80mm**	8,24° 21,68mm	12,13° 45,39mm	7,08° 48,01mm
35	4,97° 9,38mm	35	11,01° 30,90mm	4,51° 13,39mm	7.17° 41,67mm	2,12° 47,01mm
32	**12,89° 36,80mm**	11,01° 30,90mm	32	6,93° 19,09mm	12,36° 14,20mm	11,01° 26,48mm
42	8,24° 21,68mm	4,51° 13,39mm	6,93° 19,09mm	42	6,52° 31,88mm	4,09° 40,50mm
45	12,13° 45,39mm	7,17° 41,67mm	12,36° 14,20mm	6,52° 31,88mm	45	5,05° 14,27mm
47	7,08° 48,01mm	2,12° 47,01mm	11,01° 26,48mm	4,09° 40,50mm	5,05° 14,27mm	47

Figure 4. Screenshots of Precise Implant Capture (PIC) app. A, Multiunit implant abutment standard tessellation language (STL) file containing 3-dimensional implant position obtained by using stereophotogrammetry app tested. B, Linear and angular Euclidean measurements obtained in same file. Values expressed in mm correspond to Euclidean distances, while values in degrees represent angular deviation. *Red* highlight indicates critical interimplant angulation that may suggest use of angled abutment.

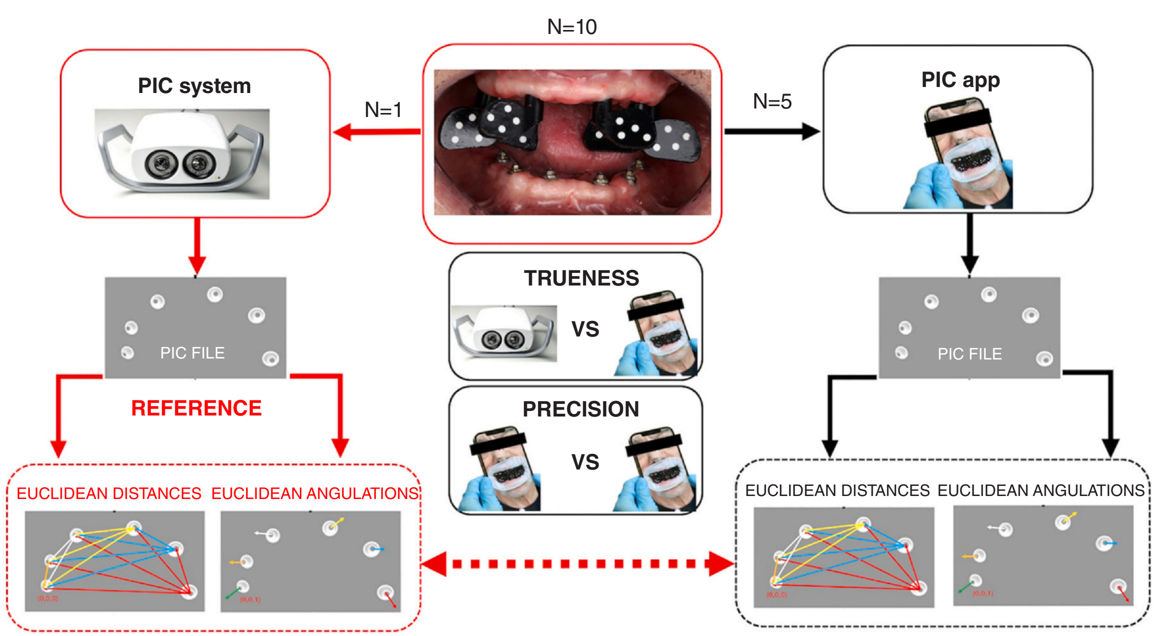


Figure 5. Study design. PIC, Precise Implant Capture.

Descriptive statistics were calculated overall, as well as stratified by participant, dental arch, and implant span. To assess the potential effect of dental arch and implant span on trueness, multivariable analyses were conducted using mixed linear models. Two separate models were fitted: one for distance deviation and another for angular deviation. In both models, dental arch and implant span were included as fixed effects, while participant was modeled as a random effect to account for intraindividual variability. Logarithmic transformation was applied after confirming nonnormality in both distance and angle deviations using the Shapiro–Wilk tests. Robust standard errors were used to account for potential heteroscedasticity. After model fitting, residual diagnostics were performed to verify the assumptions of residual normality and homoscedasticity.

Precision was evaluated based on the variability of the measurements across 5 PIC app recordings per arch. The Levene tests were used to assess the equality of

Table 1. Distance and angle trueness deviations: overall and by participant and arch

	Distance Deviation (µm)	Angle Deviation (Degrees)
Overall		
Mean ±SD	21 ±16	0.20 ±0.17
Median [p25, p75]	17 [8, 30]	0.15 [0.07, 0.28]
By Participant		
Participant 1		
Mean ±SD	20 ±14	0.19 ±0.14
Median [p25, p75]	17 [10, 30]	0.19 [0.07, 0.27]
Participant 2 (2 arches)		
Mean ±SD	23 ±17	0.19 ±0.20
Median [p25, p75]	19 [12, 32]	0.12 [0.07, 0.24]
Participant 3		
Mean ±SD	33 ±20	0.22 ±0.16
Median [p25, p75]	31 [18, 47]	0.17 [0.08, 0.35]
Participant 4		
Mean ±SD	20 ±15	0.21 ±0.20
Median [p25, p75]	18 [9, 29]	0.16 [0.06, 0.30]
Participant 5		
Mean ±SD	17 ±12	0.20 ±0.16
Median [p25, p75]	14 [8, 24]	0.16 [0.07, 0.32]
Participant 6		
Mean ±SD	17 ±13	0.22 ±0.19
Median [p25, p75]	13 [7, 27]	0.18 [0.08, 0.32]
Participant 7 (2 arches)		
Mean ±SD	19 ±15	0.16 ±0.13
Median [p25, p75]	15 [7, 30]	0.13 [0.06, 0.24]
Participant 8		
Mean ±SD	12 ±10	0.21 ±0.15
Median [p25, p75]	10 [5, 17]	0.19 [0.07, 0.32]
By dental arch		
Maxillary arch		
Mean ±SD	20 ±16	0.20 ±0.16
Median [p25, p75]	17 [8, 30]	0.16 [0.07, 0.29]
Mandibular arch		
Mean ±SD	21 ±17	0.20 ±0.20
Median [p25, p75]	17 [7, 30]	0.13 [0.06, 0.27]

SD, standard deviation
p, percentile

variances across implant spans and dental arches. All statistical analyses were carried out using a statistical software program (Stata BE 17; StataCorp) (α=.05).

RESULTS

A total of 750 distance deviations and 750 angle deviations were analyzed. Table 1 summarizes the overall distance and angle deviations, as well as data stratified by participant and dental arch (hence, the table shows the 8 participants from whom implant captures were made from 10 arches). The mixed-effects model assessing the influence of implant span and dental arch on trueness (measured as log-transformed linear deviation) and accounting for intraindividual variability is presented in Table 2. No statistically significant differences were detected between implant spans (P>.05). A statistically significant influence was found for the arch type (P<.05), with greater linear deviation observed in the maxillary arch compared with the mandibular arch (Fig. 6). In contrast, the mixed-effects model evaluating the influence of implant span and dental arch on angular trueness revealed no statistically significant effects for either factor (P>.05) (Table 3). Similarly, none of the implant spans differed significantly from the reference span (1 to 2).

The results of the Levene test showed no statistically significant differences in the variance of the linear deviations obtained from the 5 repeated scans for each arch. There were no statistically significant differences among implant spans (W_0 = 1.317; df = 14, 135; P =.205) nor between the maxillary and mandibular arches (W_0=0.019; df =1.148; P=.889), indicating that neither factor had a significant effect on the linear precision of the PIC app measurements. Conversely, when assessing the angular deviation, no statistically significant differences in variance were observed among implant spans (W_0=1.058; df=14, 135; P=.402). However, a statistically significant difference was found between arches (W_0=22.226; df=1, 148; P<.001), with lower variance in the mandibular arch than in the maxillary arch among the 5 replicates.

DISCUSSION

This study compared the PIC app with the PIC system, which had been reported to be precise under clinical conditions and unaffected by intraoral factors.[12,13,18] A recent

Table 2. Fixed effects estimate from mixed-effects model evaluating influence of dental arch and implant span on linear trueness (log-transformed distance deviation)

	Estimate	Robust Standard Error	P	95% Confidence Interval	
Intercept	2.54	0.26	<.001	2.02	3.05
Dental arch					
Maxillary (compared to Mandibular)	0.14	0.02	<.001	0.09	0.19
Implant span					
1 to 3 (compared with 1 to 2)	0.10	0.30	.734	-0.49	0.70
1 to 4 (compared with 1 to 2)	-0.11	0.39	.774	-0.88	0.66
1 to 5 (compared with 1 to 2)	-0.44	0.36	.220	-1.13	0.26
1 to 6 (compared with 1 to 2)	-0.51	0.26	.051	-1.02	0.00
2 to 3 (compared with 1 to 2)	0.14	0.33	.678	-0.51	0.78
2 to 4 (compared with 1 to 2)	0.20	0.32	.526	-0.42	0.82
2 to 5 (compared with 1 to 2)	0.10	0.33	.749	-0.53	0.74
2 to 6 (compared with 1 to 2)	-0.48	0.29	.101	-1.05	0.09
3 to 4 (compared with 1 to 2)	-0.31	0.36	.384	-1.02	0.39
3 to 5 (compared with 1 to 2)	0.10	0.38	.790	-0.64	0.85
3 to 6 (compared with 1 to 2)	-0.03	0.30	.923	-0.61	0.55
4 to 5 (compared with 1 to 2)	-0.09	0.36	.795	-0.80	0.61
4 to 6 (compared with 1 to 2)	-0.02	0.36	.964	-0.71	0.68
5 to 6 (compared with 1 to 2)	0.20	0.24	.402	-0.27	0.67

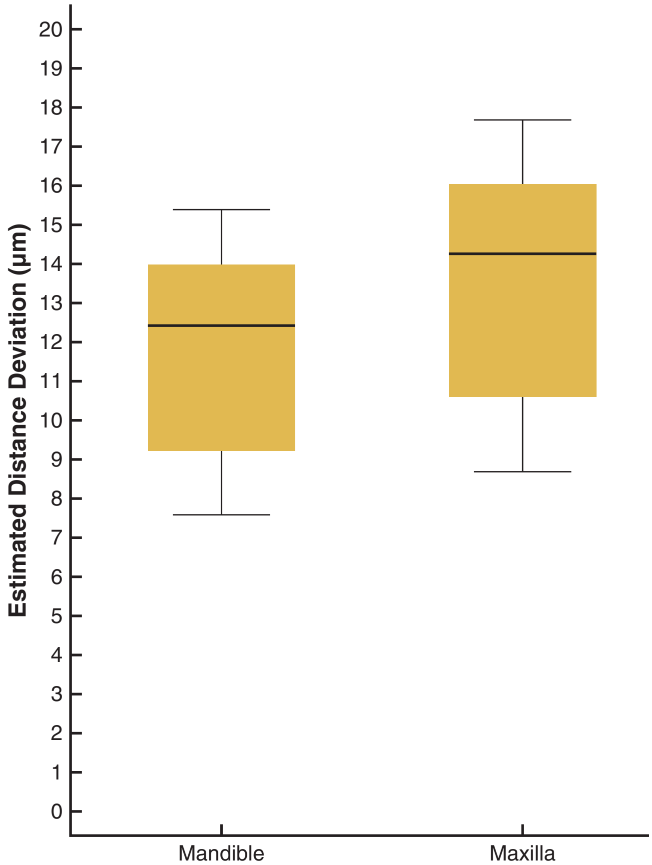


Figure 6. Box plot of estimated distance deviations by dental arch obtained from mixed-effects model after reversing log transformation.

systematic review and meta-analysis concluded that the PIC system reported higher accuracy for complete arch implant recordings than IOSs.[14] However, most available studies evaluating EPG accuracy have been conducted under simulated conditions, thus failing to address the challenges present in the clinical setting.[3,22,34,43,50]

The null hypothesis that no statistically significant differences in trueness and precision would be found among complete arch implant recordings captured with the smartphone EPG app and the EPG system was not rejected because the complete arch implant recordings captured with the smartphone EPG app and the EPG system were statistically similar (*P*>.05). The null hypothesis that the interimplant distance or the dental arch type would not affect the accuracy of the recordings was partially rejected as the interimplant distance did not significantly affect the accuracy of the captures (*P*>.05). However, a statistically significant effect (*P*<.05) was found for the arch type, since greater linear deviation in trueness and greater angular deviation in precision were observed in the maxillary arch than in the mandibular arch. Additionally, the PIC app may provide more user-friendly and economical implant recordings.

The authors are unaware of a previous clinical investigation that analyzed the accuracy of a smartphone-based system for recording implant positions. Therefore, comparisons with previous published studies were not feasible.

The metric used to assess the trueness in implant recordings significantly affected the outcome of the study. Root mean square deviation (RMS) is a commonly used metric, but it averages all discrepancies and can obscure critical errors.[52] Variations in RMS outcomes were reported to be influenced by the alignment methodology in complete arch implant recordings.[35] When all scan bodies were used to align a digital scanning, the mean trueness was 86 µm. However, aligning only the first 2 implants, as in a digital Sheffield test, revealed an error of 304 µm at the most distal implant. These findings highlight the impact of the alignment reference on the error metric outcomes and suggest that a global best fit alignment could underestimate the misfit values in complete arch scenarios.

Table 3. Fixed effects estimate from mixed-effects model evaluating influence of dental arch and implant span on angular trueness (log-transformed angle deviation)

	Estimate	Robust Standard Error	*P*	95% Confidence Interval	
Intercept	-2.33	0.26	<.001	-2.85	-1.82
Dental arch					
Maxillary (compared to Mandibular)	0.10	0.10	.310	-0.09	0.30
Implant span					
1 to 3 (compared to 1 to 2)	0.35	0.22	.105	-0.07	0.78
1 to 4 (compared to 1 to 2)	0.11	0.30	.709	-0.47	0.70
1 to 5 (compared to 1 to 2)	0.10	0.32	.748	-0.52	0.72
1 to 6 (compared to 1 to 2)	0.19	0.32	.559	-0.45	0.83
2 to 3 (compared to 1 to 2)	0.50	0.28	.072	-0.04	1.04
2 to 4 (compared to 1 to 2)	0.05	0.33	.878	-0.59	0.69
2 to 5 (compared to 1 to 2)	0.21	0.37	.562	-0.51	0.94
2 to 6 (compared to 1 to 2)	0.18	0.39	.653	-0.59	0.95
3 to 4 (compared to 1 to 2)	-0.19	0.26	.448	-0.69	0.31
3 to 5 (compared to 1 to 2)	0.07	0.17	.671	-0.26	0.40
3 to 6 (compared to 1 to 2)	0.21	0.27	.438	-0.33	0.75
4 to 5 (compared to 1 to 2)	-0.12	0.33	.715	-0.76	0.52
4 to 6 (compared to 1 to 2)	0.30	0.32	.348	-0.32	0.92
5 to 6 (compared to 1 to 2)	0.22	0.25	.372	-0.27	0.72

Conversely, interimplant Euclidean distances and angles provided precise, clinically relevant measurements independent of the alignment methods. This approach avoided the distortion caused by best fit algorithms and provided more accurate insights into implant positioning.[27] Therefore, Euclidean distances were used in the present study.

The mixed-effects model evaluating the influence of implant span on linear and angular trueness was analyzed to determine whether precision decreased with distance. This limitation has been reported previously when using IOSs, as a result of the 3D image reconstruction technology, which is based on the best fit algorithm stitching process. It has been demonstrated that the longer the scanning range, the greater the error.[27,29,40]

The results of this study showed that the trueness of the PIC app was not significantly affected by the implant span (P=.204 for linear deviation; P=.402 for angular deviation) (Tables 2, 3). These findings were consistent with Yan et al,[13] who also reported that the accuracy of EPG systems was independent of the position or number of implants. However, the interimplant scan body distance impacted the linear trueness and precision of an IPG system.[9] This impact observed in IPG systems also occurred in IOSs, where an increase in the interimplant span was associated with a decrease in accuracy.[27] However, unlike in the present study, Yan et al did not find any correlation with the arch type. In contrast, this study found statistically significant differences in trueness and precision between arches (P<.001) (Tables 2, 3). The maxillary arch showed lower precision than the mandibular arch. However, IOSs have reported better results for the maxillary arch than for the mandibular arch. Factors such as the palatal rugai, as well as increased keratinized tissue in the maxillary arch may improve the scanning precision.[41]

Although no formal sample size calculation was performed, the inclusion of 10 dental arches (consistent with previous studies),[12,23,37] each with 6 implants and 5 repeated recordings, resulted in a total of 750 distance deviations and 750 angle deviations—figures sufficiently large to estimate the linear and angular trueness of the PIC app with very small precision errors (1.28 µm and 0.01 degrees, respectively).

The PIC app was intuitive to use, but there was still a learning curve, as has been described for IOSs.[40] With experience, operators needed fewer images and less time to complete the capture. Minimizing reflections during PIC transfers and allowing a brief interval between each photograph seemed to facilitate recording with the PIC app. Additionally, since the images were uploaded in real time to the app's cloud platform, system efficiency relied on the strength of the internet connection, which could affect the duration of the procedure.[28]

The PIC app reported similar accuracy to that of the PIC system, with mean differences of 12.7 µm and 0.07 degrees. The PIC system exhibited slightly better trueness values for both linear and angular measurements.[28] The clinical implications of these statistically significant differences needed to be confirmed in clinical studies. In the present in vivo study, the PIC app showed deviations of 17 µm and 0.15 degrees compared with the PIC system (Table 1). The consistency between the results of the cited in vitro study and the present clinical research suggested that clinical conditions did not substantially impact the application's accuracy.

Limitations of this study included the relatively small sample size, although it was compensated for by the high number of recordings made by the participant. Additionally, while the study assessed the accuracy of the PIC app, it did not evaluate the actual clinical fit of a prosthesis. Although lighting conditions did not affect the PIC system because of its infrared light, the potential impact of lighting conditions on the PIC app requires further investigation. Reflections on the PIC transfers may interfere with image acquisition with the PIC app and should be evaluated through both in vitro and in vivo investigations.

Despite the limitations, the study outcomes suggested that the PIC app represents a suitable alternative to high-cost EPG and IPG systems that use image stitching. Its lower cost and portability could make digital complete arch implant recordings more accessible in clinical practice. However, future studies are needed to validate these findings by assessing the actual passive fit of prostheses fabricated with the recordings made with the PIC app. Confirming these aspects would facilitate the integration of the PIC app into routine workflows, thus expanding the implementation of EPG in prosthetic dentistry.

CONCLUSIONS

Based on the findings of this clinical study, the following conclusions were drawn:

1. The PIC app was sufficiently accurate in making recordings in complete arch implant supported prostheses with 6 implant abutments.
2. The distance between implants did not affect the accuracy of the PIC app. The arch type influenced the accuracy of the PIC app, with higher trueness and precision in the mandible.
3. Through the use of smartphones, the PIC app enables a more accessible and affordable implementation of the PIC system, without compromising accuracy.

CREDIT AUTHOR STATEMENT

Based on the 6 authors, the contribution of each is detailed as follows: A.S.L. designed the investigation, supervision, writing original draft, writing-review and editing; R.C.O. performed validation, writing-review and editing and visualization; A.M.M. data curation, measurements, writing-review and editing; J.L.Q. performed investigation and resources; C.A.V. assessed the data curation and formal analysis; J.O.P. performed the conceptualization, project administration, writing original draft, writing-review and editing.

All authors reviewed the manuscript and approved the final version.

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