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RESEARCH AND EDUCATION

Surface and linear scan accuracy of intraoral and extraoral photogrammetry systems: An in vitro study

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ABSTRACT

Statement of problem. Digital photogrammetry systems have the potential to simplify implant recording procedures and improve accuracy. Nevertheless, the surface and linear scan accuracy of these systems, particularly those using intraoral photogrammetry technology, compared with that of conventional impressions, has not been fully established.

Purpose. The purpose of this in vitro study was to evaluate the surface and linear scan accuracy (trueness and precision) of intraoral and extraoral photogrammetry systems by comparing them with conventional polyvinyl siloxane impressions for complete arch mandibular implant-supported prostheses.

Material and methods. An edentulous master mandibular stone cast with 6 implants was digitized with an industrial-grade scanner to generate its reference standard tessellation language (R-STL) file. Digital scans of the master cast were made using intraoral (Aoralscan Elite, AE) and extraoral photogrammetry systems (Icam4D, IC; OxoFit, OX), while stone casts obtained from conventional polyvinyl siloxane impressions of the master cast (CNV) were digitized with a laboratory scanner (n=20). The R-STL file and the STL files of all recordings were imported into an analysis software program to calculate the surface and linear deviations of the recording methods. While the surface deviations were analyzed with the Welch analysis of variance and Tamhane T2 tests, the linear deviations were assessed with Kruskal-Wallis and Bonferroni-adjusted post hoc tests. Precision was defined as the average of how much each measurement differed from the overall mean and was statistically analyzed with Kruskal-Wallis and Bonferroni-adjusted post hoc tests (α=.05).

Results. OX recordings had the highest surface deviations, while CNV impressions had the lowest linear deviations ($P\leq$.009). In addition, OX led to lower linear deviations than IC (P=.002). Regardless of the outcome, IC led to the lowest values when the precision of the measured deviations was considered (P<.001).

Conclusions. Although the tested recording methods showed significant differences in scan accuracy, the magnitude of deviations was small, and the deviations were within clinically acceptable thresholds. (J Prosthet Dent 2026;135:818.e1-e7)

Achieving a precise passive fit between a prosthesis and dental implants is essential for the long-term success of implant-supported restorations. Inaccuracies during clinical or laboratory procedures can lead to misfit, increasing the risk of mechanical and biological complications, including prosthesis fracture, peri-implantitis, and marginal bone loss.[1,2] Therefore, accurately transferring the implant's position from the patient to the laboratory represents a critical step in the fabrication process of an implant-supported prosthesis.[3] Even though a recent systematic review reported that mechanical complications are unlikely when vertical misfits are below 160 μm or horizontal misfits are under 150 μm and that biological complications may be avoided with vertical misfits up to 1 mm and horizontal misfits up to 345 μm,[4] clinicians should aim to minimize misfits by ensuring highly accurate digital scans or conventional impressions.

Intraoral scanners (IOSs) have become a valuable tool for fabricating implant-supported prostheses,[5,6] with studies showing accuracy comparable with that of

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Clinical Implications

The tested intraoral and extraoral photogrammetry systems can be considered suitable alternatives to conventional open-tray polyvinyl siloxane impressions for a mandibular complete arch prosthesis supported by 6 implants, as the magnitude of the significant differences across recording methods was small for all evaluated outcomes and the measured deviations remained within the clinically acceptable thresholds reported in previous studies.

conventional methods for single crowns or short-span fixed dental prostheses.[7,8] However, achieving the accuracy required for complete arch implant-supported prostheses remains challenging, as the absence of distinct anatomic landmarks in edentulous arches complicates scanning, and clinical experience highlights particular difficulties in the edentulous mandible, where limited reference points and interference from the tongue can impede accurate data capture.[9–11] Photogrammetry, a mathematical technique that generates 3-dimensional (3D) coordinates by identifying specific reference points on an object from images made at different angles,[11,12] has been proposed as an alternative for accurately capturing implant positions.[13,14] Most currently available photogrammetric devices are extraoral and require system-specific markers screwed onto each implant, which may limit their clinical practicality,[15,16] and cannot record all relevant information for designing implant-supported prostheses.[17–19] Recent developments have integrated photogrammetry into an IOS system (Aoralscan Elite; Shining 3D), allowing the intraoral recording of implant positions using dedicated scan bodies.[20–22] This approach enables the simultaneous capture of implant positions and surrounding anatomic structures, thereby streamlining digital data acquisition and providing the comprehensive dataset necessary for designing and fabricating accurate implant-supported prostheses in a single workflow.[23,24]

Recent studies have evaluated the newly introduced intraoral photogrammetry technology and reported results favorable for clinical application, highlighting its potential to improve accuracy, simplify workflows, and enhance patient comfort compared with other recording methods for implant-supported prostheses with multiple implants.[6,9,11,17,19–23,25] One of these studies[19] compared intraoral photogrammetry with conventional polyvinyl siloxane impressions; however, the comparison was limited to the duration of the procedure. Given that conventional polyvinyl siloxane impressions remain the standard for complete arch implant-supported prostheses[1,2,26–28] and that indirect digital workflows based on these impressions are still widely used worldwide because of limited access to advanced intraoral or extraoral photogrammetry scanners in many clinics, a comparison of intraoral and extraoral photogrammetry is warranted to evaluate the potential advantages and limitations of these emerging digital technologies. This study directly compared intraoral and extraoral photogrammetry systems with conventional impressions under standardized complete arch conditions to provide clinically meaningful data on their accuracy and applicability. The objective was to assess the surface and linear scan accuracy (trueness and precision) of intraoral photogrammetry, extraoral photogrammetry, and conventional polyvinyl siloxane impressions in a mandibular complete arch implant-supported situation. The null hypotheses were that the recording method would not affect the surface or linear scan accuracy of a mandibular complete arch implant-supported prosthesis.

MATERIAL AND METHODS

A completely edentulous master mandibular stone cast with 6 bone-level implants (Nobel Replace Conical Connection, 4.3×11.5 mm; Nobel Biocare) located at the right second molar, right second premolar, right canine, left canine, left second premolar, and left second molar positions was used for this study. After tightening the multi-unit abutments (Multi-Unit Abutment NP/RP; Nobel Biocare) to the implants with 35 Ncm and placing the scan bodies (Elos Accurate Scan Body 10 2C-A; Elos Medtech) manually, the model was digitized using an industrial blue-light scanner (ATOS Q 8M; Zeiss) to generate a reference standard tessellation language (R-STL) file. After generating the R-STL file, the scan bodies were removed.

For digital scans of the master mandibular cast with intraoral photogrammetry (Aoralscan Elite, AE; Shining 3D), new scan bodies (Elite Photogrammetry markers; Shining 3D) were hand tightened on each multi-unit abutment in a lingual orientation, ensuring no contact between adjacent scan bodies.[23,25] All digital scans were made in a controlled environment with stable ambient light, temperature, and humidity[14] by 1 operator (M.N.S.). Complete arch implant recordings followed the manufacturer's recommended scanning strategy for intraoral photogrammetry. The scanner was calibrated before data collection and after every scan using the manufacturer's protocol, and the scan bodies were not untightened until all recordings had been completed.[22] After completing the intraoral photogrammetry recordings, the scan bodies were replaced with extraoral photogrammetry (Icam4D Generation 5, IC; Imetric) scan bodies (ICamBodies; Imetric), and the decision to

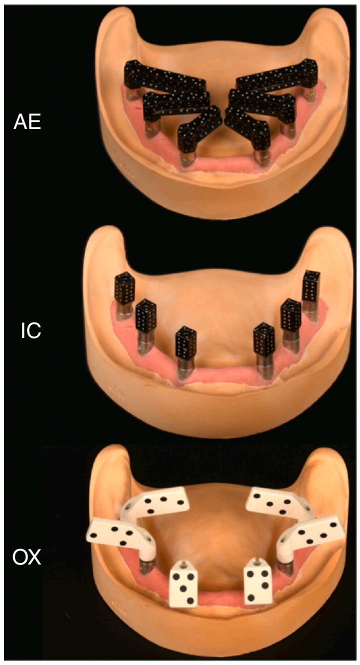

Figure 1. Master mandibular stone cast with implant scan bodies for each digital scan method tested. AE, Aoralscan Elite; IC; Icam4D; OX, OXO Fit.

start with IC was determined by a coin toss. Complete arch recordings were acquired from 25 to 30 cm, with the IC system calibrated using the manufacturer's calibration plate before each scan, and the scan bodies were not removed until all recordings had been completed. Following the IC recordings, the scan bodies were exchanged for those (Posts, MUA RP; OXO Technology) of another extraoral photogrammetry system (OxoFit, OX; OXO Technology). The scan bodies remained in place throughout all digitization procedures. Complete arch recordings were acquired from 20 to 25 cm.[23] Figure 1 shows the proprietary scan bodies for each digital scan method tested.

For the conventional impressions of the master mandibular cast (CNV), open-tray abutment-level impression copings (Impression Coping Open Tray CC RP; Nobel Biocare) were tightened to each multi-unit abutment and splinted using an autopolymerizing acrylic resin (Pattern Resin LS; GC Corp). Before making impressions with custom trays (Imibase; Imicryl) and polyvinyl siloxane impression material (Flexceed Putty Type and Flexceed Light Body; GC Corp), the resin splint was sectioned between implants and reconnected with the same acrylic resin to ensure passivity and compensate for polymerization shrinkage.[13] After the impressions had been made at room temperature, implant analogs (Implant Replica Conical Connection RP; Nobel Biocare) were secured, and the impressions were poured using low-expansion (0.08%) Type IV dental stone (New Fujirock; GC Corp). Following the manufacturer's instructions, 100 g of powder was mixed with 20 mL of water,[29] and casts were removed 40 minutes after pouring. All impression and pouring procedures were completed on the same day by the same operator (M.N.S.). The resulting stone casts were randomly (Excel; Microsoft Corp) digitized using a laboratory scanner (E4; 3Shape A/G) reported to provide high accuracy for complete arch implant-supported prostheses[30] to generate their STL files. The number of recordings per method was determined by a power analysis (α=.05, 1-β=0.95, effect size f=0.642) based on a previous study[23] indicating that 12 recordings would be sufficient. However, to increase the statistical power, 20 recordings were performed per method.

After completion of all recordings, the STL files (1 R-STL and 80 test-scan STLs) were imported into a dental design software program (exocad DentalCAD; exocad GmbH). In each file, the scan bodies were substituted with multi-unit abutments,[17] as their geometry facilitated superimposition and deviation measurements. The multi-unit abutments were virtually isolated in each STL, and the processed STLs were imported into a metrology-grade analysis software program (Geomagic Control X 2020.1; 3D Systems), recommended by the International Organization for Standardization 12836 standard,[31] for deviation analysis. R-STL was imported as the reference dataset, and each test-scan STL was superimposed using initial and iterative closest point best-fit alignment methods.[11,13] Three-dimensional surface deviations were quantified through the root mean square method.[17] In addition, color maps were generated with the software program's "3D Compare" function, with deviation limits set at ±100 µm and a tolerance range of ±10 µm (Fig. 2).[13] For linear deviation analysis, a circle was defined on the occlusal surface of each multi-unit abutment in every STL file using the

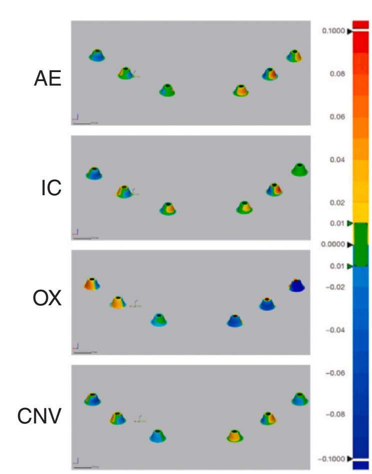

Figure 2. Representative color maps of each recording method. AE, Aoralscan Elite; CNV, conventional polyvinyl siloxane; IC; Icam4D; OX, OXO Fit.

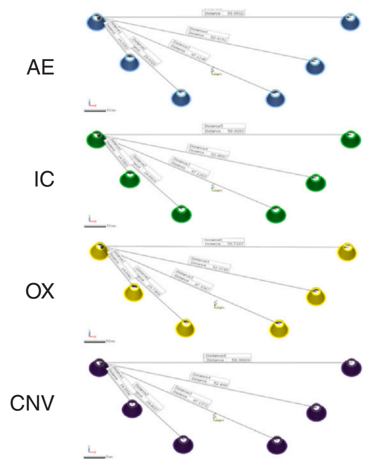

Figure 3. Representative Euclidian distance measurements of each recording method. AE, Aoralscan Elite; CNV, conventional polyvinyl siloxane; IC; Icam4D; OX, OXO Fit.

software program's "Add circle" tool. Then, the center of each virtual circle was marked using the "Add Point" tool, and the Euclidean distances[6,19,21–23] between the right second molar abutment and the other abutments were measured in each STL with the software program's "Measure Distance" function (Fig. 3). The absolute difference between the R-STL and each test-scan STL was calculated for every abutment pair, and the arithmetic mean of those values was taken as that STL's linear deviation.

The normality and homogeneity of surface and linear deviation data were examined using the Shapiro-Wilk and Levene tests, respectively. Surface deviations showed normal but heterogeneous distributions, whereas linear deviations deviated from normality. Consequently, surface deviations were analyzed with the Welch analysis of variance followed by Tamhane T2 tests, while linear deviations were evaluated using the Kruskal-Wallis test with Bonferroni-adjusted post hoc comparisons. Precision was determined from the mean deviation, defined as the arithmetic average of the absolute differences between individual values and the group mean, and was further assessed with the Kruskal-Wallis test and Bonferroni-adjusted post hoc analyses. All statistical analyses were performed with a software program (IBM SPSS Statistics, v26; IBM Corp) (α=.05).

RESULTS

Significant differences were observed among tested recording methods for both surface and linear accuracy outcomes (P<.001). OX resulted in the highest surface deviations (P<.001), while the differences among the remaining recording methods were not statistically significant (P≥.057). When the precision of the surface deviations was considered, IC led to the lowest deviations (P<.001) and the differences among other recording methods were not statistically significant (P>.05) (Table 1). CNV led to the lowest linear deviations (P≤.009). In addition, IC led to higher deviations than OX (P=.002). When the precision of the linear deviations was considered, IC led to the lowest deviations (P<.001) (Table 2). Figure 4 shows the box plot graphs of measured deviations.

Table 1. Mean ±standard deviation (95% confidence intervals, trueness) and median (minimum-maximum, precision) surface deviation values (µm)

Recording method	Surface deviations (Trueness)	Surface deviations (Precision)
AE	35.3 ±4.0^{a} (33.4-37.2)	2.8^{b} (0.2-8.6)
IC	37.9 ±0.4^{a} (37.7-38.1)	0.2^{a} (0.0-1.1)
OX	66.9 ±7.8^{b} (63.3-70.6)	4.1^{b} (0.8-17.2)
CNV	34.4 ±6.0^{a} (31.6-37.2)	4.2^{b} (0.5-10.4)

Different superscript lowercase letters indicate significant differences in columns (P<.05).

Table 2. Median linear deviation values (minimum-maximum) of tested recording methods (µm)

Recording method	Trueness	Precision
AE	90.1^{bc} (71.3-109.6)	6.7^{b} (1.2-19.5)
IC	94.2^{c} (92.1-96.4)	0.7^{a} (0.1-2.4)
OX	77.3^{b} (44.4-106.3)	10.7^{b} (1.1-31.9)
CNV	37.7^{a} (23.8-82.0)	7.8^{b} (2.4-38.6)

Different superscript lowercase letters indicate significant differences in columns (P<.05).

DISCUSSION

IC recordings had higher surface accuracy than OX recordings and had more precise surface deviations than AE and CNV recordings. When the linear deviations were considered, CNV impressions had the highest trueness, whereas IC recording had the highest precision. Based on these findings, the null hypotheses that the recording method would not affect the surface or linear scan accuracy of a mandibular complete arch implant-supported prosthesis were rejected.

Even though statistically significant differences were found among the tested recording methods, measured surface and linear deviations were below previously reported thresholds for mechanical and biological complications.[4] In addition, the maximum statistically significant mean and median differences (32.5 and 56.5 µm, respectively) highlight the importance of

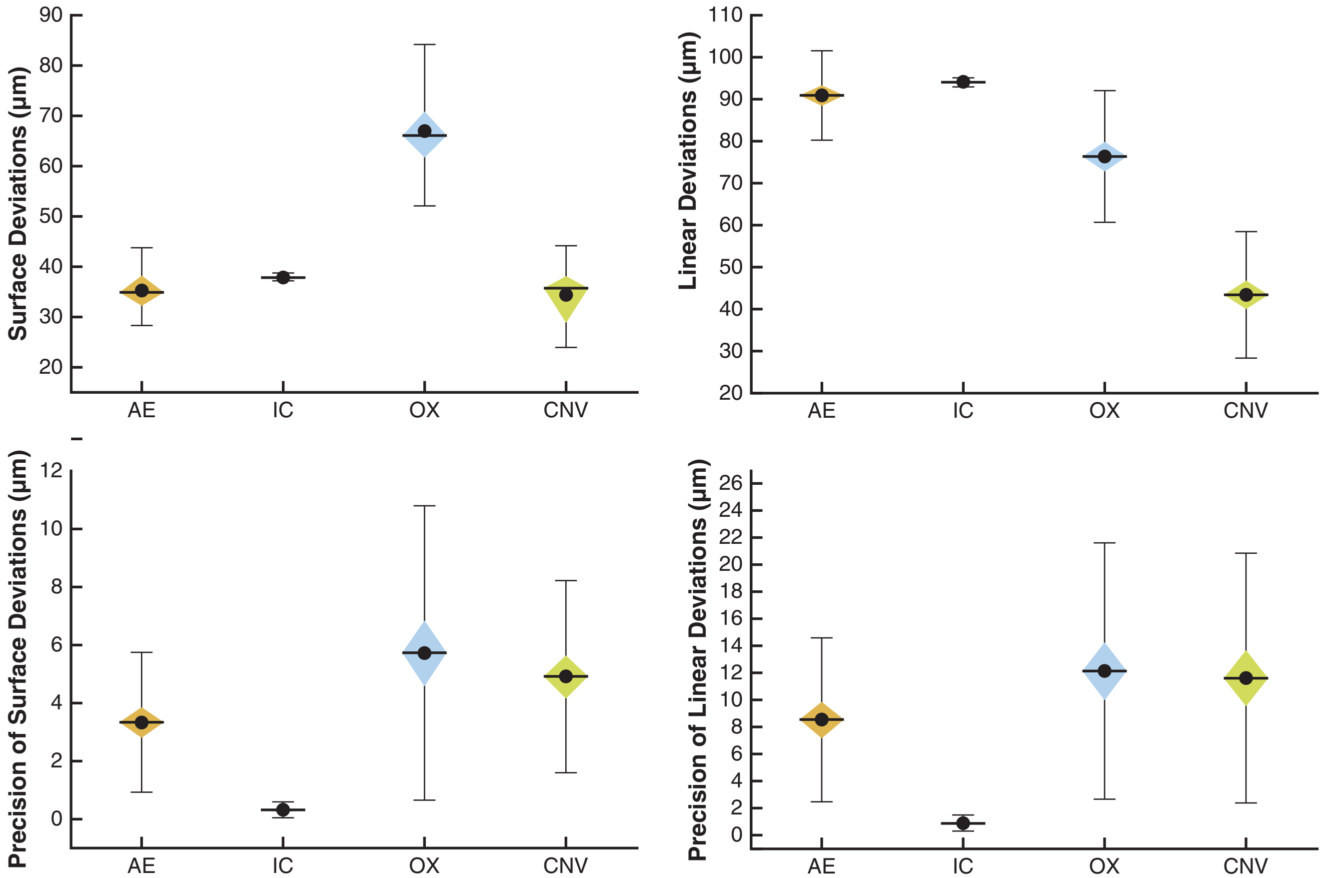

Figure 4. Box plot graphs of measured surface and linear deviations (trueness and precision) for each recording method. AE, Aoralscan Elite; CNV, conventional polyvinyl siloxane; IC; Icam4D; OX, OxoFit.

considering clinical relevance, as these values are relatively small and may not be clinically significant. These interpretations, along with the finding that the greatest median deviation for precision was only 10.7 μm and that the maximum statistically significant differences for precision were even smaller, support the suitability of the tested intraoral and extraoral photogrammetry systems as alternatives to conventional open-tray polyvinyl siloxane impressions for the evaluated situation. While systematic reviews on intraoral photogrammetry are currently lacking, potentially related to its recent introduction, Gómez-Polo et al[15] systematically reviewed extraoral photogrammetry systems and concluded that they provide accurate alternatives to conventional impressions for recording the 3D positions of dental implants, consistent with the findings of the present study.

Intraoral photogrammetry has recently gained attention, with several studies assessing its scan accuracy in both in vivo[9,19,25] and in vitro[11,17,21–23] settings. One in vivo study retrospectively compared the accuracy of intraoral photogrammetry scans with that of 2 intraoral scanners (Primescan and i900), both with and without a scanning aid.[9] The authors[9] reported that intraoral photogrammetry provides a reliable alternative and that scanning aids can enhance the accuracy of intraoral scanners. Eldabe et al[19] reported that, regardless of arch type, intraoral photogrammetry demonstrated promise for scanning implants for complete arch implant-supported prostheses, providing higher accuracy than the evaluated intraoral scanner (Aoralscan 3) and greater efficiency than conventional polyvinyl siloxane impressions. Revilla-León et al[25] concluded that all tested recording methods fell within clinically acceptable limits after comparing intraoral photogrammetry scans with those from an extraoral photogrammetry system (Micron Mapper) using snap-on markers and from an intraoral scanner (TRIOS 5) with noncalibrated horizontal scan bodies. In vitro studies consistently indicated that intraoral photogrammetry provided accuracy and reliability for complete arch implant recordings, with deviations well below clinically acceptable thresholds.[11,17,21–23] The potential of using the system across varying interimplant scan body distances, which offers workflow efficiency and positioning flexibility, has also been highlighted.[22]

The registration accuracy of soft tissue scans while using the intraoral photogrammetry system has been investigated.[6,20] In one of those studies,[20] the AE scanner was compared with IC, OX, and an additional extraoral photogrammetry system (Grammee), and the authors reported that the choice of photogrammetry system did not influence the registration accuracy of soft tissue or implant position scans. The other study[6] reported that the AE scanner performed comparably with intraoral scanners (Lumina, TRIOS 5, Primescan, and i700) for soft tissue and implant position scans in an implant workflow and noted that the manufacturer's proprietary coded healing abutments may be preferable to conventional healing abutments or implant scan bodies. Even though the present and previous studies support intraoral photogrammetry as a reliable method for complete arch implant-supported prostheses, further clinical validation is needed, as even minimal deviations, while within acceptable limits, may accumulate across multiple implants and lead to prosthesis misfit, compromised screw stability, increased mechanical stress, and potentially adverse long-term outcomes.

Limitations of this study included its standardized in vitro design, which did not account for patient- or environment-related variables that could influence the accuracy of digital or conventional impressions. In addition, conventional polyvinyl siloxane impressions were made at room temperature, thereby not modeling the thermal contraction that occurs when impressions cool from intraoral to laboratory temperatures[14]; this has been reported to reach approximately 56 μm in the anterior region and 33 μm in the posterior region.[32] Although the tested intraoral and extraoral photogrammetry systems are relatively new, and the only currently available intraoral system on the dental market was evaluated in this study, the inclusion of 3 photogrammetry systems represents another limitation. Measured deviations, irrespective of the evaluated outcome, were reported as mean or median values across all implants, and the absence of a more detailed analysis at each individual implant site was another limitation. The methodology used in the present study, which included the best-fit algorithm, surface deviations quantified by root mean square values, linear deviations measured using the Euclidean distance formula, and a metrology-grade software program, was consistent with previous investigations on the scan accuracy of intraoral and extraoral photogrammetry systems.[1,11,16,17,26] Nevertheless, the method used to calculate or quantify deviations, the alignment approach applied during superimpositions, and the software program used may influence the measured deviations. Finally, variations in clinical situations, including the number of implants, interimplant distances, implant angulations, and arch type, may also influence the measured deviations, particularly under actual clinical conditions. Future in vivo studies should aim to evaluate how the deviations observed with the tested scanners influence the fabrication accuracy and fit of complete arch implant-supported frameworks across a range of clinical situations, including variations in the number and position of implants, arch type, and patient-related factors such as oral environment and tissue characteristics, thereby providing a more comprehensive understanding of how these scanning systems perform under actual clinical conditions.

CONCLUSIONS

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

1. Tested recording methods influenced both surface and linear scan accuracy in a mandibular complete arch implant-supported prosthesis with 6 implants.
2. Tested intraoral photogrammetry system recordings had similar surface accuracy to conventional open-tray polyvinyl siloxane impression, while one of the extraoral photogrammetry systems (IC) showed higher surface accuracy than the other extraoral photogrammetry system (OX). In addition, intraoral photogrammetry recordings demonstrated similar linear scan trueness or precision to the other recording methods.
3. The magnitude of the significant differences across recording methods was small for all evaluated outcomes in the tested situation, and the measured deviations remained within the clinically acceptable thresholds reported in previous studies.

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CRediT authorship contribution statement

Mehmet Necip Selvi: Investigation, Methodology. **Mustafa Borga Donmez**: Writing - original draft, Writing - review & editing. **Münir Demirel:** Investigation. **Almira Ada Diken Türksayar**: Formal analysis.

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