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Original Research

# Accuracy of intraoral scanners and photogrammetry for full-arch implant-supported rehabilitations: an in vitro study

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ABSTRACT

***Objectives:*** This in vitro study aimed to compare the accuracy of intraoral scanning and photogrammetry-based acquisition methods for full-arch implant-supported rehabilitations involving four and six implants.

***Methods:*** An acrylic edentulous mandible was used to simulate the clinical setting. Implant positions were acquired 20 times per condition using five intraoral scanners with polyetheretherketone (PEEK) and titanium scan bodies, one photogrammetry-capable intraoral scanner, and three dedicated photogrammetry systems. Implant replicas were generated and analyzed using reverse-engineering software. Linear (µm) and angular (°) discrepancies were calculated to assess trueness and precision. Linear mixed-effects models were applied separately for linear and angular discrepancies, with impression method, implant configuration, and their interaction as fixed effects.

***Results:*** Mean linear trueness discrepancies ranged from 35.76 to 403.51 µm. Impression method significantly influenced linear and angular discrepancies ($p < 0.001$). Implant configuration had a significant effect, with higher discrepancies observed with six implants. No significant interaction was detected between impression method and implant configuration. Most photogrammetry-based systems showed lower discrepancies than the intraoral scanners, although substantial device-specific variability was observed. No consistent trend favoring PEEK or titanium scan bodies was observed.

***Conclusions:*** Impression method and implant configuration significantly influenced impression accuracy. Photogrammetry-based systems generally showed lower discrepancies, although device-specific performance should be considered when interpreting accuracy. Six-implant configurations, which involved a greater scanning span, were associated with lower accuracy. Further clinical studies are needed to determine whether these differences are clinically relevant. (Rev Port Estomatol Med Dent Cir Maxilofac. 2026;67(x):1-11)



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## Introduction

Full-arch implant-supported rehabilitation is a well-established treatment option for edentulous patients or those presenting hopeless dentition.[1,2] Dental implants are surgically placed and rehabilitated with screw or cement-retained complete-arch prostheses, providing predictable long-term outcomes. The literature reports survival rates ranging from 83.8% to 96.3%, with overall success closely related to achieving a passive prosthetic fit, which is essential to minimize biological and/or technical complications.[2]

Accurate transfer of implant positions to the working model is therefore critical for achieving passive fit in implant-supported rehabilitations.[3] Although no universal guidelines define acceptable implant misfit, previous studies have suggested vertical discrepancies between 30 µm and 160 µm and horizontal discrepancies up to 150 µm as comparative reference thresholds, as well as 1° angle divergence.[2,4,5] Exceeding these limits may result in biological complications such as mucositis and peri-implantitis, as well as mechanical complications including screw loosening and prosthesis fracture.[6] The International Organization for Standardization (ISO) 5725-1 defines accuracy as a measure of trueness and precision, with the former referring to the closeness to the true value and the latter to the degree of variability between repeated measurements.

Conventional open-tray impressions using splinted impression copings and elastomeric materials remain the gold standard for complete-arch implant impressions. Although this workflow is technique-sensitive, time-consuming, and labor-intensive, it is the most extensively validated method for full-arch implant-supported rehabilitations.[7]

In the last decade, digital and computer-aided design/computer-aided manufacturing (CAD/CAM) technologies have significantly influenced prosthodontic workflows. Intraoral scanners (IOSs) and implant-specific scan bodies of various geometries and materials have been introduced, offering more efficient and patient-friendly alternatives to conventional impressions.[8,9] These systems have demonstrated high accuracy for single-unit and short-span implant-supported restorations.[10] However, their accuracy for full-arch implant rehabilitations remains controversial due to factors such as cumulative image-stitching errors, limited intraoral reference landmarks, scanning strategies, ambient lighting conditions, and scan body design.[11-13] Recent systematic reviews and meta-analyses have reported mean accuracy discrepancies exceeding 150 µm when IOSs are used for complete-arch impressions compared to conventional impressions.[14] Thus, manufacturers have been improving superimposition algorithms in IOSs and the manufacturing processes of scan bodies in terms of components and materials.[9]

Photogrammetry systems have been introduced to directly capture the three-dimensional spatial relationship between implants. Unlike IOSs, photogrammetry devices are not affected by cumulative stitching errors and rely on simultaneous image acquisition of implant positions. These systems also require an additional soft tissue scan or impression to integrate peri-implant soft tissue morphology.[8]

The purpose of this in vitro study was to evaluate the influence of impression method, implant configuration, and scan body material on the linear and angular accuracy of complete-arch implant digital impressions. Accuracy was assessed as linear (µm) and angular (°) discrepancies relative to an industrial scanner reference and interpreted against previously reported comparative reference thresholds.[2,4,5] Consistent with the statistical model, in which impression method was operationalized as a fourteen-level factor, the null hypotheses were that impression method, implant configuration, and their interaction would not significantly influence linear or angular discrepancies; and, within the IOS subset, that scan body material and its interaction with implant configuration would not significantly influence accuracy.

## Materials and methods

This in vitro study followed a previously validated experimental protocol.[8] An experienced oral surgeon placed six bone-level tapered dental implants (Bone Level Tapered Implant; Institut Straumann AG, Basel, Switzerland) in an acrylic resin edentulous mandible with simulated pink silicone gingiva (4010G; Demobone), according to the Caramês Classification Class IA.(1) Straight screw-retained multiunit abutments (SRA RC screw-retained abutment; Institut Straumann AG) were tightened to the implants following the manufacturer's recommendations, simulating a complete-arch implant-supported master cast.

To obtain the digital reference casts, polyetheretherketone (PEEK) abutment-level scan bodies (Straumann CARES; Institut Straumann AG) were tightened to each abutment according to the manufacturer's recommendations, and the cast was digitized with a calibrated high-resolution reference scanner (ATOS Capsule scanner; GOM GmbH), which served as the gold standard. The master cast was digitized (n = 6) with six scan bodies to simulate an all-on-6 prosthesis and with four scan bodies located more anteriorly to simulate an all-on-4 prosthesis.(1) As reported in a previous study, the industrial scanner was validated and showed variability below 3 µm.[8] Therefore, one scan of the six-implant configuration and one scan of the four-implant configuration were randomly selected using a computer-generated random number and used as the reference master scans for all subsequent comparisons.

Two scan body materials were compared: PEEK (Straumann CARES, Institut Straumann AG) and titanium (Medentika SRA46; Medentika GmbH, Hügelsheim, Germany). Five IOSs were tested: TRIOS 3 (3Shape A/S, Copenhagen, Denmark), iTero Element 5D (Align Technology, Inc, San Jose, CA, USA), Medit i700 (Medit Corp, Seoul, South Korea), Virtuo Vivo (Institut Straumann AG), and Sirios (Institut Straumann AG). Each device performed scans under four experimental conditions: four implants with PEEK scan bodies, four implants with titanium scan bodies, six implants with PEEK scan bodies, and six implants with titanium scan bodies. Thus, four acquisition conditions were tested with each scanner, for a total of 20 conditions assessed by intraoral scanning.

Four systems were used in photogrammetry mode, including the Aoralscan Elite (SHINING 3D Tech Co., Ltd., Hangzhou, China) IOS operated exclusively in photogrammetry mode and three dedicated photogrammetry devices: iCam (iMetric 4D SA, Courgenay, Switzerland), PIC (PIC dental, Torrelodones, Madrid, Spain), and Oxocore (Akura Medical, Madrid, Spain). The cor-

responding proprietary photogrammetric targets were used according to each manufacturer's instructions. Photogrammetry scans were performed over four-implant and six-implant configurations. Because scan body material is not applicable to photogrammetry-based acquisition, it was not accounted for. Thus, two acquisition conditions were assessed with each system, for a total of 8 conditions tested by photogrammetry.

Based on a pilot study, the sample size calculation was performed using G*Power 3.1 (Heinrich Heine University, Düsseldorf, Germany), assuming α = 0.05, power = 0.80, and effect size f = 0.25 based on pilot data, resulting in a minimum of 18 scans per group. Thus, each condition was repeated 20 times by the same calibrated operator, for a total of 560 scans (Appendix A). Because all digital implant replicas had identical visual properties, the operator was blinded to device and condition during the measurement process.

For each acquisition, the corresponding scan body library files were aligned to the recorded scan body surfaces in CAD software (Exocad DentalCAD; Exocad GmbH), and digital implant replicas were automatically positioned. The resulting standard tessellation language (STL) files were then imported into a reverse-engineering software (Geomagic Control X; 3D Systems) where the implant center and long axis were determined for linear and angular quantitative evaluations (Figure 1). A previously described protocol was followed: linear measurements between the center of each implant in all possible com-

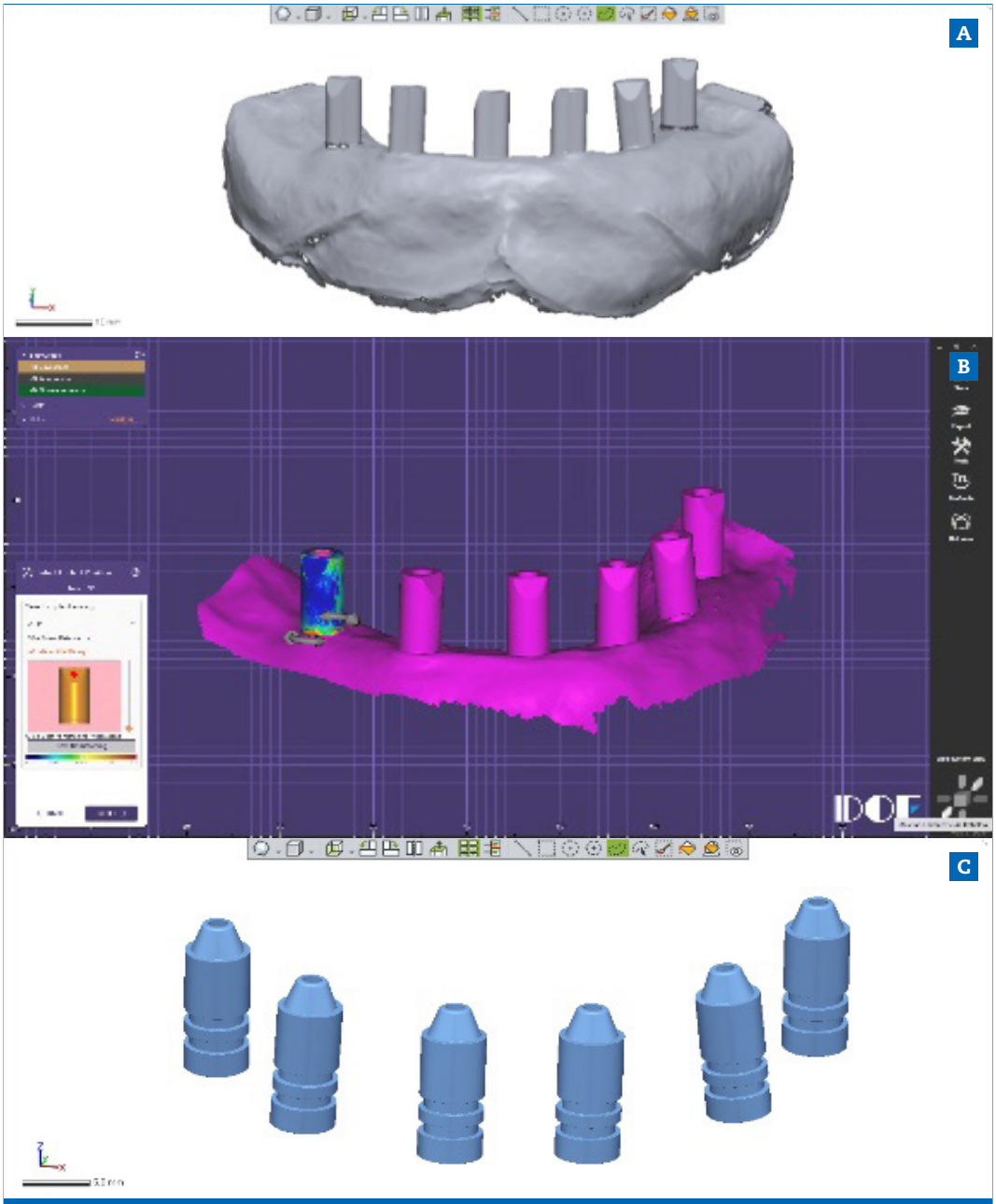


**Figure 1. Representation of the workflow. A) digital impression over six implants. B) matching scan bodies in Exocad. C) digital implant analogs for linear analysis.**

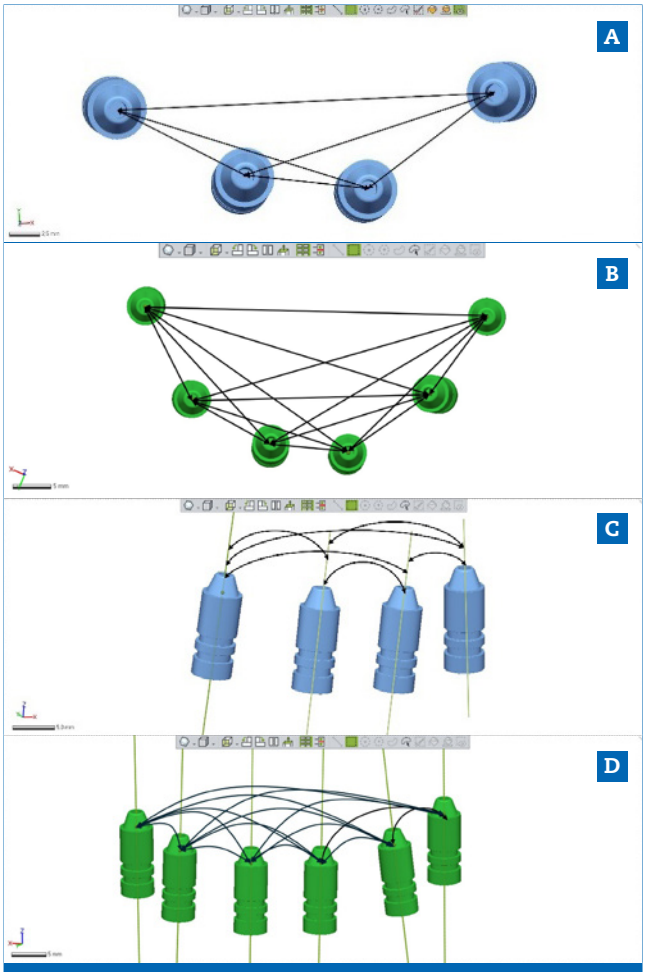


**Figure 2. Representation of linear and angular measurements. A and B, linear distances between implants. C and D, angular measurements between implant axes.**

binations and angular measurements between each implant's long axis, resulting in multiple pairwise measurements: for the 4-implant configuration, 6 inter-implant distances and 6 inter-implant angles; for the 6-implant configuration, 15 distances and 15 angles (Figure 2).[15]

The unit of analysis for all inferential models was the individual pairwise measurement, clustered within ScanID (560 acquisitions; 5880 pairwise linear and 5880 pairwise angular measurements). Trueness was calculated per device, implant configuration, and scan body condition as the mean absolute discrepancy across all pairwise measurements for that condition; precision was calculated as the standard deviation of the 20 scan-level mean absolute discrepancies for the same condition. Comparative reference thresholds (150 µm; 1°), adopted from the literature, were used as descriptive benchmarks — not as validated clinical limits, since they derive from marginal-misfit/framework-fit studies and their equivalence to inter-implant center-to-center discrepancy is unestablished — to calculate the percentage of measurements at or below these values (≤150 µm, ≤1°) for each condition.[8,4,5]

Linear mixed-effects models were fitted separately for linear and angular discrepancies, with impression method (a 14-level factor: one level per photogrammetry device and one level per the combination of IOS and scan body material), implant configuration, and their interaction as fixed effects, and ScanID as a random intercept to account for within-scan correlation. Models were estimated by REML; global effects were tested using Type III tests, reported as F-statistics with Satterthwaite-approximated degrees of freedom. Marginal and conditional pseudo-$R^2$ were computed per Nakagawa and Schielzeth, and the adjusted intraclass correlation coefficient was calculated as the ratio of between-scan (random-intercept) to total (between-scan + residual) variance.[16] All observations were included in the primary analysis. Extreme outliers (>Q3 + 3×IQR, defined separately for each outcome) were excluded in sensitivity analyses, which included a scan-level analysis (mean absolute discrepancy per scan as the unit of analysis, n = 560) using the same two-factor design.

Because photogrammetry systems do not use conventional scan bodies, the effect of scan body material (PEEK vs. titanium) was evaluated exclusively within the IOS subset. Non-parametric comparisons were performed using the Mann–Whitney U test, and a two-way fixed-effects factorial analysis of variance (ANOVA; Type III sums of squares), testing for scan body material, implant configuration, and their interaction. Device-related differences within the IOS and photogrammetry subsets were explored with the Kruskal–Wallis test and Bonferroni-adjusted pairwise comparisons, performed on both individual pairwise measurements and, as a sensitivity analysis, scan-level mean discrepancies, since the former does not account for within-scan clustering. All confirmatory inference relies on the mixed-effects models described above. Significance was set at $\alpha = 0.05$, and analyses used IBM SPSS Statistics, version 29.0 (IBM Corp).

## Results

Tables 1 and 2 present trueness and precision outcomes for linear and angular discrepancies, respectively. Based on the published literature, comparative reference thresholds of 150 µm for linear discrepancies and 1° for angular discrepancies were adopted.[2,4,5] Table 3 summarizes the frequency of linear and angular measurements below these comparative reference thresholds, and Figures 3 and 4 depict the distributions of the individual linear and angular discrepancy measurements.

For IOSs, linear trueness values ranged from 45.65 µm to 148.51 µm, with precision values ranging from 33.89 µm to 130.10 µm. Angular discrepancies ranged from 0.13° to 0.44° for trueness and from 0.05° to 0.22° for precision. Most IOS conditions remained below the predefined linear threshold on average. The proportion of individual measurements below 150 µm varied across devices and implant configurations, particularly in six-implant scans.

For systems used in photogrammetry mode, linear trueness values ranged from 35.76 µm to 403.51 µm, with precision values from 25.40 µm to 355.25 µm. Angular discrepancies ranged from 0.20° to 0.86° for trueness and from 0.11° to 0.71° for precision. The lowest linear discrepancy was observed for iCam in the four-implant configuration. Three of the four systems used in photogrammetry mode showed comparatively

**Table 1. Overall accuracy of linear measurements across the different conditions.**

| Technology | Device | Number of implants | Scan body | Trueness (µm) | Precision (µm) |
|---|---|---|---|---|---|
| Intraoral scanner | TRIOS 3 | 6 | PEEK | 138.97 | 91.20 |
| | | 6 | Titanium | 84.82 | 75.00 |
| | | 4 | PEEK | 45.65 | 39.04 |
| | | 4 | Titanium | 65.68 | 45.38 |
| | iTero | 6 | PEEK | 85.48 | 88.67 |
| | | 6 | Titanium | 88.15 | 69.43 |
| | | 4 | PEEK | 50.27 | 44.27 |
| | | 4 | Titanium | 77.91 | 38.46 |
| | Medit i700 | 6 | PEEK | 64.30 | 34.17 |
| | | 6 | Titanium | 76.40 | 35.41 |
| | | 4 | PEEK | 53.74 | 33.89 |
| | | 4 | Titanium | 59.59 | 35.74 |
| | Virtuo Vivo | 6 | PEEK | 148.51 | 130.10 |
| | | 6 | Titanium | 115.23 | 78.30 |
| | | 4 | PEEK | 73.02 | 49.67 |
| | | 4 | Titanium | 97.31 | 57.65 |
| | Sirios | 6 | PEEK | 81.61 | 56.95 |
| | | 6 | Titanium | 61.26 | 44.76 |
| | | 4 | PEEK | 55.80 | 42.42 |
| | | 4 | Titanium | 55.03 | 34.50 |
| Photogrammetry | iCam | 6 | N/A | 54.35 | 38.28 |
| | | 4 | N/A | 35.76 | 25.40 |
| | PIC Dental | 6 | N/A | 105.94 | 74.15 |
| | | 4 | N/A | 72.23 | 54.71 |
| | Oxocore | 6 | N/A | 372.85 | 239.64 |
| | | 4 | N/A | 403.51 | 355.25 |
| | Aoralscan Elite | 6 | N/A | 65.49 | 46.88 |
| | | 4 | N/A | 50.24 | 36.82 |

**Table 2. Overall accuracy of angular measurements across the different conditions.**

| Technology | Device | Number of implants | Scan body | Trueness (°) | Precision (°) |
|---|---|---|---|---|---|
| Intraoral scanner | TRIOS 3 | 6 | PEEK | 0.35 | 0.16 |
| | | 6 | Titanium | 0.28 | 0.15 |
| | | 4 | PEEK | 0.19 | 0.07 |
| | | 4 | Titanium | 0.21 | 0.12 |
| | iTero | 6 | PEEK | 0.19 | 0.09 |
| | | 6 | Titanium | 0.28 | 0.12 |
| | | 4 | PEEK | 0.13 | 0.05 |
| | | 4 | Titanium | 0.20 | 0.10 |
| | Medit i700 | 6 | PEEK | 0.44 | 0.22 |
| | | 6 | Titanium | 0.33 | 0.20 |
| | | 4 | PEEK | 0.28 | 0.20 |
| | | 4 | Titanium | 0.23 | 0.22 |
| | Virtuo Vivo | 6 | PEEK | 0.31 | 0.18 |
| | | 6 | Titanium | 0.32 | 0.20 |
| | | 4 | PEEK | 0.30 | 0.22 |
| | | 4 | Titanium | 0.24 | 0.22 |
| | Sirios | 6 | PEEK | 0.30 | 0.19 |
| | | 6 | Titanium | 0.33 | 0.18 |
| | | 4 | PEEK | 0.23 | 0.17 |
| | | 4 | Titanium | 0.26 | 0.22 |
| Photogrammetry | iCam | 6 | N/A | 0.33 | 0.18 |
| | | 4 | N/A | 0.20 | 0.11 |
| | PIC Dental | 6 | N/A | 0.38 | 0.22 |
| | | 4 | N/A | 0.22 | 0.13 |
| | Oxocore | 6 | N/A | 0.86 | 0.48 |
| | | 4 | N/A | 0.77 | 0.71 |
| | Aoralscan Elite | 6 | N/A | 0.33 | 0.19 |
| | | 4 | N/A | 0.24 | 0.19 |

**Table 3. Frequency of measurements at or below the comparative reference thresholds for the tested devices in the different conditions.**

| Device | Number of implants | Scan body | Measurements ≤150 µm (%) | Measurements ≤1° (%) |
|---|---|---|---|---|
| **TRIOS 3** | 6 | PEEK | 63.67 | 96.67 |
| | 6 | Titanium | 84.67 | 100.00 |
| | 4 | PEEK | 99.17 | 100.00 |
| | 4 | Titanium | 94.17 | 100.00 |
| **iTero** | 6 | PEEK | 80.67 | 98.67 |
| | 6 | Titanium | 82.33 | 99.67 |
| | 4 | PEEK | 93.33 | 100.00 |
| | 4 | Titanium | 89.17 | 100.00 |
| **Medit i700** | 6 | PEEK | 92.33 | 88.33 |
| | 6 | Titanium | 88.67 | 99.33 |
| | 4 | PEEK | 100.00 | 99.17 |
| | 4 | Titanium | 96.67 | 100.00 |
| **Virtuo Vivo** | 6 | PEEK | 66.33 | 99.00 |
| | 6 | Titanium | 74.00 | 99.33 |
| | 4 | PEEK | 89.17 | 97.50 |
| | 4 | Titanium | 83.33 | 99.17 |
| **Sirios** | 6 | PEEK | 82.67 | 99.67 |
| | 6 | Titanium | 90.33 | 99.00 |
| | 4 | PEEK | 93.33 | 100.00 |
| | 4 | Titanium | 97.50 | 100.00 |
| **iCam** | 6 | N/A | 93.33 | 100.00 |
| | 4 | N/A | 100.00 | 100.00 |
| **PIC Dental** | 6 | N/A | 70.67 | 93.33 |
| | 4 | N/A | 83.33 | 100.00 |
| **Oxocore** | 6 | N/A | 49.00 | 76.33 |
| | 4 | N/A | 55.00 | 79.17 |
| **Aoralscan Elite** | 6 | N/A | 88.00 | 100.00 |
| | 4 | N/A | 100.00 | 100.00 |

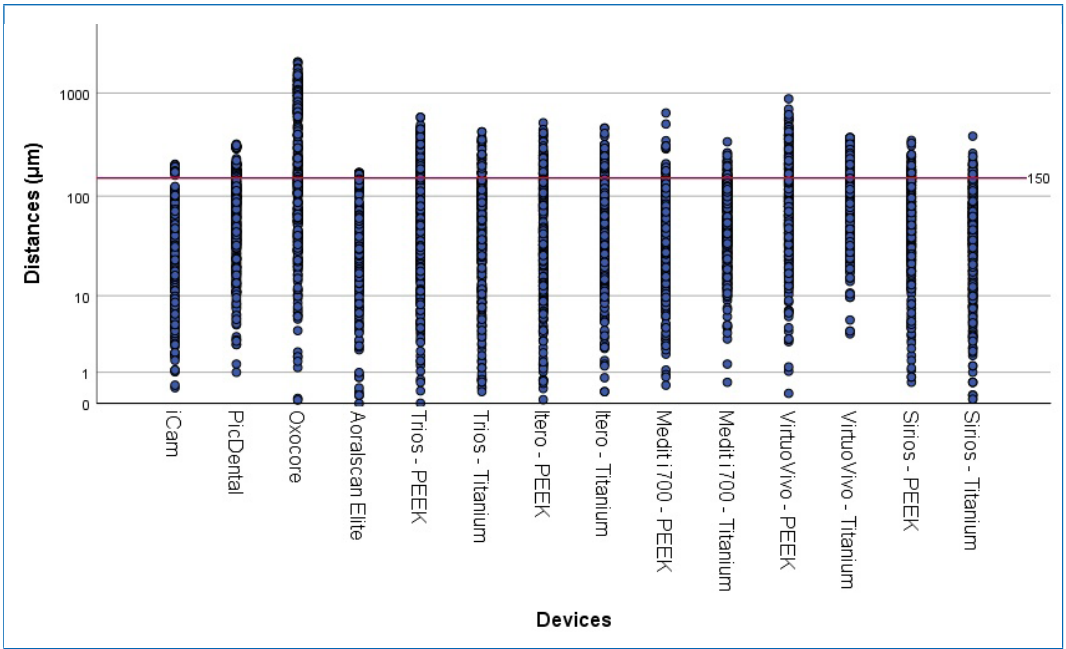


**Figure 3. Distribution of linear discrepancies for the tested digital acquisition methods. Comparative reference threshold at 150 µm. The vertical axis is presented on a logarithmic scale.**

low discrepancies, whereas Oxocore showed substantially higher discrepancies and greater variability. For Oxocore, the median linear discrepancies were 129.83 µm (interquartile range 43.31–745.91 µm) in the four-implant configuration and 156.27 µm (interquartile range 60.17–595.61 µm) in the six-implant configuration.

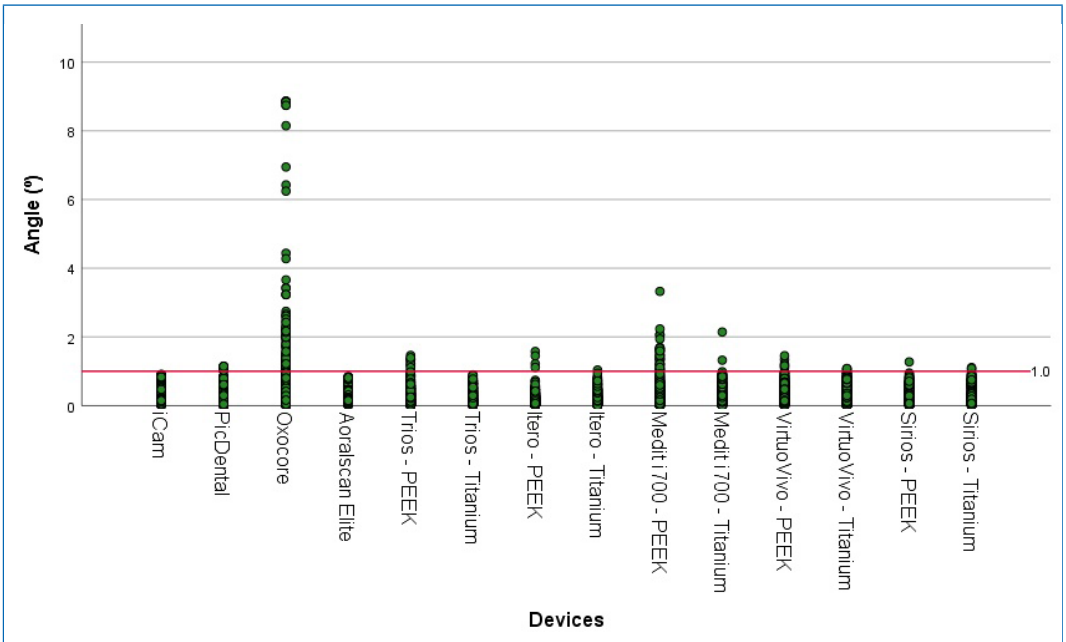


**Figure 4. Distribution of angular discrepancies for the tested digital acquisition methods. Comparative reference threshold at 1°.**

The percentage of measurements below the comparative reference thresholds followed the same general pattern. For linear discrepancies, iCam and Aoralscan Elite showed high proportions of measurements below 150 µm, whereas Oxocore showed the lowest percentage of measurements within the linear threshold in both implant configurations (49.00% and 55.00% for six- and four-implant configurations, respectively). For angular discrepancies, most devices showed high percentages of measurements below 1°, although Oxocore again showed the lowest threshold compliance.

Table 4 summarizes inferential statistics derived from the linear mixed-effects models. For linear discrepancies, impression method had a significant effect, $F(13, 536.25) = 30.21$, $p < 0.001$. Implant configuration also had a significant effect, $F(1, 536.25) = 8.88$, $p = 0.003$, with higher discrepancies observed in six-implant configurations. The interaction between impression method and implant configuration was not significant, $F(13, 536.25) = 0.91$, $p = 0.538$. Regarding angular discrepancies, impression method had a significant effect, $F(13, 563.58) = 16.71$, $p < 0.001$. Implant configuration significantly influenced angular discrepancies, $F(1, 563.58) = 23.18$, $p < 0.001$, again with higher discrepancies in six-implant configurations. No significant interaction was detected between impression method and implant configuration, $F(13, 563.58) = 0.35$, $p = 0.984$. The effect of implant configuration was stronger for angular than for linear discrepancies.

**Table 4. Linear mixed-effects model results for absolute inter-implant linear and angular discrepancies.**

| Effect / Model parameter | Linear discrepancy, Dist (µm) | Angular discrepancy, Ang (°) |
|---|---|---|
| **Impression method** | $F(13, 536.25) = 30.21$, $p < 0.001$ | $F(13, 563.58) = 16.71$, $p < 0.001$ |
| **Implant configuration, 4 vs 6 implants** | $F(1, 536.25) = 8.88$, $p = 0.003$ | $F(1, 563.58) = 23.18$, $p < 0.001$ |
| **Impression method × implant configuration** | $F(13, 536.25) = 0.91$, $p = 0.538$ | $F(13, 563.58) = 0.35$, $p = 0.984$ |
| **Marginal pseudo-$R^2$** | 0.247 | 0.111 |
| **Conditional pseudo-$R^2$** | 0.552 | 0.284 |
| **Adjusted ICC** | 0.405 | 0.195 |
| **Random effect** | ScanID random intercept | ScanID random intercept |
| **Between-scan (ScanID) variance** | 8303.72 µm² | 0.0367 degrees² |
| **Residual variance** | 12185.54 µm² | 0.1516 degrees² |

Impression method, implant configuration, and their interaction were fixed effects.
ScanID (560 scans) was included as a random intercept.
Marginal and conditional pseudo-$R^2$ were calculated according to Nakagawa and Schielzeth; $\alpha = 0.05$.
ICC, intraclass correlation coefficient.

The random intercept for ScanID was retained in both models to account for the clustered structure of repeated measurements within each scan. The estimated between-scan (ScanID) variance was 8303.72 μm² for linear discrepancies and 0.0367 degrees² for angular discrepancies, with residual variances of 12,185.54 μm² and 0.1516 degrees², respectively. The corresponding adjusted intraclass correlation coefficients were 0.405 for linear discrepancies and 0.195 for angular discrepancies.

In the scan-level sensitivity analysis, in which the mean absolute discrepancy of each scan was used as the unit of analysis (n = 560), the two-factor analysis reproduced the mixed-effects results. For linear discrepancies, impression method, $F(13, 532) = 30.09$, $p < 0.001$, and implant configuration, $F(1, 532) = 8.84$, $p = 0.003$, were significant, whereas their interaction was not, $F(13, 532) = 0.91$, $p = 0.541$. For angular discrepancies, impression method, $F(13, 532) = 16.69$, $p < 0.001$, and implant configuration, $F(1, 532) = 23.15$, $p < 0.001$, were significant, whereas their interaction was not, $F(13, 532) = 0.35$, $p = 0.984$.

Extreme outliers (>Q3 + 3×IQR) accounted for 187/5880 (3.2%) observations for linear and 83/5880 (1.4%) for angular measurements and were excluded in sensitivity analyses. When stratified by subset, outlier exclusions corresponded to 137/1680 (8.2%) for linear and 58/1680 (3.5%) for angular measurements in the photogrammetry subset, and 50/4200 (1.2%) for linear and 25/4200 (0.6%) for angular measurements in the IOS subset. After exclusion of extreme outliers and recalculation of the scan-level means, impression method and implant configuration remained significant predictors of linear discrepancy, $F(13, 529) = 4.57$, $p < 0.001$, and $F(1, 529) = 31.24$, $p < 0.001$ (n = 557 scans; three Oxocore four-implant scans were excluded because all their measurements were extreme outliers), and of angular discrepancy, $F(13, 532) = 5.16$, $p < 0.001$, and $F(1, 532) = 29.65$, $p < 0.001$. The interaction remained non-significant for both outcomes, $F(13, 529) = 1.45$, $p = 0.132$, and $F(13, 532) = 0.63$, $p = 0.833$.

As a robustness check, non-parametric sensitivity analyses (Kruskal–Wallis with Bonferroni-adjusted pairwise comparisons) performed on the individual pairwise measurements corroborated the presence of device-specific differences within both the IOS subset and the photogrammetry subset (Appendix A). When these analyses were repeated on the scan-level mean discrepancies, device-related differences remained significant within both subsets (IOSs: $H(4) = 19.19$, $p < 0.001$ for linear and $H(4) = 13.25$, $p = 0.010$ for angular discrepancies; photogrammetry: $H(3) = 64.37$, $p < 0.001$ for linear and $H(3) = 30.82$, $p < 0.001$ for angular discrepancies), although the test statistics were substantially lower than in the measurement-level analysis and several pairwise comparisons within the IOS subset no longer reached significance (Tables A2 and A3).

Because scan body material applies only to IOSs, additional analyses were performed within the IOS subset. Pooled non-parametric comparisons revealed no statistically significant differences between PEEK and titanium scan bodies for linear or angular discrepancies, whether evaluated at the measurement level (Mann–Whitney: linear, $p = 0.259$; angular, $p = 0.227$), or scan-level means (linear, $p = 0.211$; angular, $p = 0.726$). In a two-way fixed-effects factorial ANOVA restricted to the IOS subset, with scan body material, implant configuration, and their interaction as factors, implant configuration remained a significant predictor for both outcomes (linear: $F(1, 4196) = 114.44$, $p < 0.001$; angular: $F(1, 4196) = 91.40$, $p < 0.001$), whereas the main effect of scan body material was not significant for linear ($F(1, 4196) = 0.30$, $p = 0.582$) or angular measurements ($F(1, 4196) = 0.33$, $p = 0.568$). The interaction between scan body material and implant configuration was significant for linear ($F(1, 4196) = 34.28$, $p < 0.001$) but not for angular measurements ($F(1, 4196) = 0.56$, $p = 0.453$).

## Discussion

This in vitro study compared the accuracy of different digital acquisition technologies and devices for full-arch implant-supported rehabilitations using linear and angular discrepancy measurements. Based on the results, the null hypotheses regarding impression method and implant configuration were rejected, as both factors significantly influenced linear and angular discrepancies. Regarding scan body material, sensitivity analyses based only on IOS acquisitions did not support a consistent overall main effect on linear or angular discrepancies, although configuration-dependent differences in linear discrepancy cannot be excluded. Overall, the results indicate that the acquisition technology/device and implant configuration are the main factors influencing complete-arch digital impression accuracy.

Statistically significant differences were observed among the evaluated devices, confirming that accuracy is highly method- and device-dependent and not uniform across acquisition systems. Although most systems in photogrammetry mode presented favorable results, Oxocore showed high variability and the lowest proportions of measurements below the reference thresholds of both linear (49.00–55.00%) and angular discrepancies (76.33–79.17%). Implant number significantly affected accuracy, with six-implant configurations exhibiting higher discrepancies than four-implant configurations. The lack of a significant interaction between impression method and implant configuration indicates no statistical evidence that the effect of each method differed substantially between four- and six-implant configurations. For the Oxocore device, the mean linear discrepancy was higher in the four-implant than in the six-implant configuration, contrary to the overall trend. This inversion is attributable to a markedly right-skewed error distribution with extreme outliers in that condition, since the corresponding median values indicated the expected direction of greater discrepancy with increasing implant number; these device-specific mean values should therefore be interpreted together with the underlying error distribution.

Most photogrammetry devices showed lower linear and angular discrepancies than the IOSs. This observation should nevertheless be interpreted with caution, because the mixed-effects models did not include a formal contrast between the photogrammetry and IOS categories, and one photogrammetry device (Oxocore) showed higher discrepancies than all the IOSs tested. These findings corroborate previous in vitro and in vivo investigations reporting that photogram-

metry is less susceptible to cumulative stitching errors and provides a more stable spatial capture of implant positions in complete-arch scenarios.[17-20]

Regarding IOSs, the additional analyses based only on IOS acquisitions did not support a consistent overall effect of scan body material on either linear or angular discrepancies. In pooled non-parametric comparisons, PEEK and titanium scan bodies showed no statistically significant differences for linear or angular discrepancies. In the IOS-only factorial ANOVA, implant configuration remained a significant predictor for both outcomes, whereas scan body material was not a significant main effect. Notably, linear discrepancies showed an interaction between scan body material and implant configuration, suggesting that any material-related differences in linear error may be configuration-dependent rather than uniform. Taken together, these findings indicate that, under the present in vitro conditions, device-specific performance and scanning span appear to exert a more consistent influence on accuracy than scan body material alone, and any potential material-related effects should be interpreted cautiously and within the context of implant configuration and scanner system.[9,13]

The present findings are supported by previously published studies, as several in vitro and in vivo investigations have reported superior or more predictable accuracy of photogrammetry compared with intraoral scanning in complete-arch implant scenarios.[17] Previous studies demonstrated that photogrammetry outperformed both intraoral scanning and conventional impressions in capturing implant positions, although posterior soft tissue acquisition was required to align implant position data.[18,19] Improved framework passivity has also been reported in a prospective in vivo study.[20] Systematic reviews have also highlighted that IOSs are validated for single-tooth and short-span prostheses but remain less predictable for complete-arch applications.[7,10] The current results reinforce these conclusions by showing that several IOS conditions, particularly in six-implant configurations, presented a relevant proportion of measurements above the comparative reference threshold of 150 µm, in line with previous findings.[11,21] Photogrammetry-based recording of implant positions is inherently free from the sequential image-stitching errors that affect intraoral scanning.[22]

The high variability observed among photogrammetry devices indicated that not all systems perform equivalently despite sharing similar underlying principles. This heterogeneity is clinically relevant because it shows that the technology category alone is insufficient to predict accuracy. Device-specific factors such as calibration protocols, optical triangulation quality, camera configuration, scan body or marker design, and software best-fit algorithms should be considered when evaluating the performance of each system.

The observed statistically significant reduction in accuracy with an increased number of implants is consistent with previous reports describing cumulative error propagation in full-arch digital impressions.[8,10-12] The clinical relevance of these discrepancies remains unclear and should be tested in vivo. Minor discrepancies may fall within the comparative reference thresholds and may not necessarily compromise short-term outcomes. Cumulative inaccuracies may affect long-term prosthetic passivity and biomechanical stability, particularly in complete-arch rehabilitations. In this context, the adopted thresholds of 150 µm and 1° should be interpreted as comparative reference values based on previous literature rather than as universally accepted clinical limits. Mean trueness values should therefore be interpreted alongside the threshold-based analyses, because conditions with acceptable mean discrepancies may still present a relevant proportion of individual measurements above the reference threshold. The effect of implant configuration was numerically stronger for angular than for linear discrepancies, suggesting that an increased scanning span may have a greater impact on angular deviation between implant axes.

From a methodological perspective, the internal validity of this study is strengthened by the use of a validated industrial-grade optical scanner to obtain reference measurements (ATOS Capsule scanner), the random selection of the reference master scan from repeated acquisitions of a scanner with previously documented within-scanner variability below 3 µm, calibration of the operator, and an optimized methodology that minimizes inaccuracies related to inferring abutment positions for these highly precise measurements.[8] The use of mixed-effects models further allowed the analysis to account for within-scan correlation, and a scan-level sensitivity analysis using the mean discrepancy of each scan as the unit of analysis reproduced the same effects, confirming that the reported significance was not an artifact of the number of pairwise measurements obtained from each scan. Nevertheless, the magnitude of the non-parametric test statistics decreased markedly when the scan was used as the unit of analysis, and several pairwise device comparisons within the IOS subset no longer reached significance; measurement-level pairwise comparisons should therefore be interpreted as exploratory.

This study's external validity is limited by its in vitro design. Clinical conditions introduce additional variables such as saliva, restricted intraoral access, patient movement, reflective surfaces, prosthetic space limitations, and soft tissue dynamics, which may influence impression accuracy. The results were also obtained from a standardized mandibular model and may not fully represent the variability of clinical anatomy, implant angulation, mucosal conditions, and interarch space observed in daily practice.

Although statistically significant differences were observed, their clinical relevance should be interpreted cautiously and within the broader context of full-arch implant-supported rehabilitation. The absence of clinical validation of the observed differences, particularly regarding prosthesis passivity, complication rates, peri-implant biological outcomes, and long-term implant success, remains a limitation of the present study.

## Conclusions

Within the controlled in vitro conditions of this study, impression method and implant configuration significantly influenced the accuracy of complete-arch implant position re-

cording. Most photogrammetry devices showed lower discrepancies than the IOSs; however, substantial device-specific variability was observed, indicating that performance should not be inferred solely from the acquisition technology category. Six-implant configurations, which involved a greater scanning span, were associated with higher linear and angular discrepancies than four-implant configurations. Within the IOS subset, scan body material did not show a significant overall main effect on linear or angular discrepancies; any potential material-related differences in linear discrepancy may depend on configuration. Further clinical studies are needed to determine whether such differences translate into clinically meaningful outcomes.

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## Conflict of interest

The authors have no conflicts of interest to declare.

## Ethical disclosures

**Protection of human and animal subjects.** The authors declare that no experiments were performed on humans or animals for this study.

**Confidentiality of data.** The authors declare that no patient data appear in this article.

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## CRediT authorship contribution statement

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## Exatidão dos scanners intraorais e fotogrametria em reabilitações implanto-suportadas de arcada completa: estudo *in vitro*

RESUMO

***Objetivos:*** Comparar a exatidão de scanners intraorais e de sistemas de fotogrametria em reabilitações implantossuportadas de arcada completa com quatro e seis implantes.
***Métodos:*** Foi utilizada uma mandíbula acrílica edêntula para simular a situação clínica. As posições dos implantes foram adquiridas 20 vezes por condição com cinco scanners intraorais (scan bodies em PEEK e titânio), um scanner intraoral em modo de fotogrametria e três sistemas de fotogrametria. As discrepâncias lineares (µm) e angulares (°) foram calculadas em software de engenharia inversa para avaliar veracidade e precisão. Foram aplicados modelos lineares de efeitos mistos separadamente para discrepâncias lineares e angulares, com método de impressão, configuração dos implantes e respetiva interação como efeitos fixos.
***Resultados:*** As discrepâncias lineares médias de veracidade variaram entre 35,76 e 403,51 µm. O método de impressão influenciou significativamente as discrepâncias lineares e angulares ($p < 0,001$). A configuração dos implantes teve um efeito significativo, com maiores discrepâncias com seis implantes. Não foi detetada interação significativa entre método de impressão e configuração dos implantes. A maioria dos sistemas de fotogrametria apresentou menores discrepâncias do que os scanners intraorais, embora com variabilidade substancial entre dispositivos. Não se observou tendência a favor de PEEK ou titânio.
***Conclusões:*** O método de impressão e a configuração dos implantes influenciaram significativamente a exatidão. Os sistemas de fotogrametria apresentaram, em geral, menores discrepâncias, embora o desempenho de cada dispositivo deva ser considerado. As configurações de seis implantes, com maior extensão de digitalização, associaram-se a menor exatidão. São necessários estudos clínicos para confirmar a relevância clínica destas diferenças. (Rev Port Estomatol Med Dent Cir Maxilofac. 2026;67(x):xxx-xxx)


***Palavras-chave:***
Desenho Assistido por Computador
Implantes Dentários
Impressão sobre implantes
Tecnologia Digital
Fotogrametria