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Critical methodological factors influencing the accuracy of intraoral scanners in digital dentistry research

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ABSTRACT

This in vitro study aimed to identify the key methodological factors influencing the accuracy of intraoral scanners (IOS). The primary factors analyzed included the length of the scanned area, the total number of alignment points, the software used for analysis, and the operator's expertise. Three IOS systems were assessed—CEREC Primescan, Trios 3, and Omnicam—along with a laboratory desktop scanner (inEos X5). Scans were performed on a mandibular typodont, with the Root Mean Square (RMS) error used to measure the discrepancies between reference and experimental scans. The results indicated that the length of the scanned area significantly affected the RMS values, with full-arch scans producing greater errors compared to those of quadrant scans. Additionally, the total number of alignment points in the standard tessellation language files positively influenced accuracy, although improvements plateaued beyond 20 points. The choice of processing software also impacted accuracy, with Geomagic Control X yielding significantly lower RMS values than those of MeshLab and CloudCompare. Finally, user expertise played a significant role in scanning accuracy, with the experience user achieving more precise results, especially when using the Trios 3 scanner.

Thus, the length of the scan, number of alignment points, software tools, and operator expertise significantly influence the accuracy of IOS, highlighting the importance of considering these methodological factors in both clinical and research settings for digital impressions.

1. Introduction

The scientific dental community has developed digital instruments to evaluate the accuracy of computer-aided design/computer-aided manufacturing (CAD/CAM) restorations [1,2] using various intraoral scanner (IOS) systems [3–5], different dental tissue preparation configurations [6,7], comparisons between conventional and digital impressions [8], and assessments of IOS accuracy under varying conditions [9]. The majority of published studies have used the standard tessellation language (STL) output from the IOS system and measured differences using metrology-grade or reversed engineering software, comparing the control digital impression with the impression being evaluated. Studies conducted on this topic have yielded varied results, with some indicating the technique is less effective, while others suggest it is superior to traditional impression-taking methods [10]. These differences may be attributed to factors such as the device used, the size of the scanned area, the scanning method, the substrate, user experience, ambient light, and scanner calibration. Moreover, the alignment method in CAD software has been another area of investigation in several studies [11–16].

Digital scans are used with CAD software to create accurate designs for crowns, bridges, and various prosthetic or orthodontic devices. Root mean square (RMS) error is employed to check the accuracy of digital designs by comparing them to the intended restorations, allowing for adjustments to ensure an optimal fit and function. Furthermore, RMS error quantifies the mismatch between digital models and their corresponding 3D-printed physical outputs, ensuring that the final restorations and orthodontic appliances meet stringent clinical requirements [17].

In digital dentistry, RMS error serves as a fundamental quantitative tool, providing insights into the accuracy and precision of digital scans, CAD/CAM designs, and 3D-printed dental prosthetics. By advancing technology and adhering to rigorous validation protocols, dental practitioners can minimize RMS errors, thereby enhancing treatment outcomes and patient satisfaction in contemporary dental practice.

Although published works offer guidance for researchers to conduct methodologically sound studies in dental materials [18,19], and for dentists to enhance the accuracy of digital impressions and IOS use [20,

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21], in vitro research in digital dentistry lacks standardization because of the relatively recent introduction of these technologies. Consequently, many researchers make methodological errors, and journal reviewers often overlook these shortcomings. Few studies have been published on the factors affecting the accuracy of IOS [20,21], with most of these studies focusing on the clinical application of the results rather than providing guidance for researchers. Key considerations in the research include the type of scanner used for digitizing intraoral tissue, whether the digitization will be performed in vitro or in vivo, the number of alignment points when comparing STL files, the length of the scan, available lighting conditions, the operator's experience, and the software programs used for comparing the STL files. Accurate performance of IOS is crucial for reliable outcomes in modern dental workflows, including prosthetics, orthodontics, and restorative treatments. Digital impressions are significantly influenced by various methodological factors such as scan length, alignment points, software tools, and operator expertise; however, their combined effects remain underexplored. The accuracy of IOS is essential for precise diagnosis and treatment planning across all areas of digital dentistry, including prosthetics, orthodontics, and implant-related procedures. Incorrect scanning usually results in poor-quality digital impressions and suboptimal preoperative and postoperative outcomes. Although the use of IOS technology has increased, there has been limited systematic research evaluating the methodological factors that affect scanner performance. Factors such as the scan length, number of alignment points, software analysis tools, and operator expertise significantly influence the accuracy and precision of digital impressions. However, a critical gap remains in understanding how these methodological factors affect scanner accuracy. Understanding these variables will lead to clinical workflow optimization and better reliability in digital diagnostics in dentistry. A systematic study of these variables will help advance the dental research community's knowledge of their combined effects, thus leading to improvements in digital workflows and the refinement of reliable diagnostic protocols. With the continued advancement of digital dentistry, understanding these factors is crucial for enhancing workflows, ensuring clinical accuracy, and driving further research. Therefore, this study aimed to fill this gap by systematically reviewing the basic underlying elements of the discipline, thus creating a valuable resource for practitioners and researchers in the field. To determine the accuracy of the IOS, this study used computational tools and algorithms as the core components of a methodological strategy. Advanced software platforms, such as Geomagic Control X, CloudCompare, and Meshlab, were used for mesh analysis, alignment processes, and error quantification. These computer science-based tools, which are based on computer science principles, enable precise measurement of discrepancies and play a key role in understanding the performance of digital scanning technologies in dentistry.

This in vitro study investigated the primary factors affecting the accuracy of IOS. It was hypothesized that the length of the scanned area (Ho1), total number of alignment points (Ho2), software used for analysis (Ho3), and the IOS operator's expertise (Ho4) would not influence the RMS values between the reference and examined scan areas.

2. Materials and methods

In this study, three IOS were used: CEREC Primescan (Dentsply Sirona), TRIOS (3Shape), and CEREC Omnicam (Dentsply Sirona), in addition to an inEos X5 (Dentsply Sirona) desktop scanner. Each scanner utilizes different technology to digitize dental tissues. The first IOS employed advanced technology for the digitization of dental tissues, featuring high-resolution sensors and short-wave light, combined with optical high-frequency contrast analysis, to enable dynamic deep-scan capabilities. Trios 3 uses confocal microscopy and ultrafast optical sectioning, while Omnicam utilizes active triangulation (multicolor stripe projection). The laboratory desktop scanner employs digital light-stripe projection. The three IOS were selected based on their widespread adoption and clinical relevance to both research and practice. These devices represent a range of scanning technologies including confocal microscopy (Trios 3), active triangulation (Omnicam), and optical high-frequency contrast analysis (Primescan). This diversity ensures the coverage of various scanning principles while maintaining comparability under standardized conditions. The inEos X5 desktop scanner, which serves as a benchmark for evaluating IOS systems, was included as a reference device because of its high accuracy. Although newer or less common scanners were not included in this study, the selected systems represented a significant proportion of the currently utilized digital workflows in dentistry.

For all experiments assessing factors influencing scanner accuracy, a dental simulation mannequin (P-Oclusal, São Paulo, Brazil) with Typodont jaws (Flex-Manequim Odontológico, P-Oclusal, São Paulo, Brazil) was employed to simulate the oral condition of a dentate individual requiring an indirect crown restoration on tooth #36. This mannequin included removable and replaceable soft gums and teeth. On the mandibular typodont, within the posterior left quadrant, the initial molar was removed and substituted with the factory-made crown-prepared tooth #36. The maxillary typodont assembly was digitized using a single methodology—the utilization of a customized parallelometer (Mestra Surveyor, Talleres Mestraitua, SL Mestra, Spain). A customized parallelometer was used to stabilize the mandibular typodont both horizontally and at various angles during the IOS scanning process. This instrument, in conjunction with the maxillary typodont assembly, ensured consistent scanning levels and distances for all IOS utilized in this study. The selected IOS was calibrated before its initial use and subsequently after every six scans, according to the manufacturer's recommended protocol. During the intraoral scanning process, ambient illumination was consistently maintained at 1000 lux, as measured using a luxmeter (Smart Sensor, ST9620; EMIN Myanmar Co., Singapore). Intraoral digital scans were performed by an experienced operator (P. M.) with over 10 years of expertise in using IOS and more than 1500 manufactured CAD/CAM restorations. A 20-min rest period was provided after every six scans to mitigate operator exhaustion. The scans were subjected to a meticulous visual inspection to confirm accurate and satisfactory registration. This process was repeated to generate 30 test scans, which were subsequently exported as standard tessellation language (STL) files. Previous studies have indicated that altering the scanning patterns can influence the accuracy of intraoral digital scans [22,23]. The scanning pattern refers to the specific sequence used to capture an intraoral digital scan, and it is generally recommended to follow the scanning protocol provided by the manufacturer of the selected IOS [24].

In this study, the standardized scanning protocol provided by each manufacturer was followed for all IOS. This approach aimed to ensure consistency and minimize operator-related variability. While sequence variation and starting point selection were not independently evaluated, these factors remained significant contributors to scan accuracy, as noted in prior studies [22]. The scanning protocol was standardized to focus on the primary methodological factors influencing IOS accuracy.

The RMS error quantifies the degree of correspondence between digital scans and the actual anatomical structures, which crucially affects the fit and durability of dental restorations. RMS error is a statistical measure used to quantify the magnitude of variation or discrepancy in a set of values. It is commonly applied in engineering, physics, and statistics fields to assess the accuracy of measurements and predictions. RMS error is calculated as the square root of the mean of the squares of a set of values, providing a single value that represents the average magnitude of the difference between the corresponding values of two datasets. RMS error was calculated for a specified area using the following formula:

$RMS = \sqrt{\{(1/n)\, \Sigma_{(i=1^n)}\, (X_{1,i} - X_{2,i})^2\}}$ where:

- $X_{1,i}$ represents reference data points,

- $X_{2,i}$ represents scan data points, and
- n indicates the total number of measurement points for each analysis.

This comprehensive application of RMS in digital dentistry underlines its pivotal role in smoothing clinical workflows and improving the quality of dental care. Calculations for the discrepancy in each subgroup were used for the analysis. In contrast to general arithmetic means, RMS provides a more reliable and accurate value as it squares the difference of each data point from the mean, accounting for both positive and negative deviations [25].

Trueness was quantified as the mean RMS error discrepancy between the reference file and experimental scans, while precision was characterized by the RMS error variation within each group, expressed as the standard deviation [26].

The control scans produced by the desktop lab scanner served as a reference for measuring the discrepancy values with the experimental scans across the various tested groups. Color maps showing three-dimensional deviations were generated after superimposition (Figs. 7-9). The maximum and minimum critical values were set at +50 μm and −50 μm, respectively, while the tolerance range was set between +10 μm and −10 μm. These values were represented as positive (over contoured) or negative (under contoured) areas within the software [27]. Four groups were established based on the investigated factors. The first factor was the length of the scanned area; the second was the total number of alignment points used for RMS measurements; the third involved the software analysis programs, and the final factor evaluated the proficiency of the IOS operator.

2.1. Factor: length of scanned area

The scan span can significantly affect the accuracy of IOS, making it essential to consider this factor when selecting the appropriate scanner for a specific clinical case. When scanning large areas, merging multiple individual images can result in gradual distortion and a subsequent decrease in accuracy within the dataset [28,29]. Conventional impressions are often preferred for long-span cases because of their superior accuracy [30]. However, recent studies on updated IOS hardware and software versions indicate that digital scans are more suitable for long-span cases [31]. The efficiency of various IOS can differ significantly because of their respective scanning technologies and features, particularly in situations with long-span restorations and small convergence angles [15,32].

To evaluate the length of the scanned area, two approaches were used: a) scanning the entire dental arch and b) scanning the quadrant with the prepared tooth. The scanning methodology provided by each IOS manufacturer was consistently applied to all digital impressions, regardless of whether the entire dental arch or quadrant of the dentition was scanned.

2.2. Factor: total number of alignment points

Various 3D datasets that are aligned and compared to evaluate the trueness and precision of IOS are complex and prone to errors. The mathematical complexities of aligning this dataset are mostly hidden from the users for ease of use. These complexities can have a significant impact on the accuracy assessment of IOS, which has not been extensively discussed in dental literature. The simplest way to align two datasets is to utilize an Iterative Closest Point (ICP) matching algorithm [12]. This algorithm iteratively determines the closest point pairs between two point sets and applies a rigid transformation that aligns them. Many enhancements have been made to the ICP algorithm in recent decades; however, it still converges to an optimum alignment that is highly dependent on the quality of the initial alignment. Studies have found that substantial alignment errors can occur when superimposing scanned structures using ICP algorithms. However, it has been suggested that if an initial alignment is performed with 10 control points, each having an error under 0.5 mm, these errors are minimized [33]. To evaluate the total number of alignment points, three approaches were used: a) four alignment points, b) 10 control points, c) 20 control points, and d) 30 alignment points.

2.3. Factor: different software analysis program

Measurements of the RMS values were provided using the most popular metrology software applications: MeshLab, CloudCompare, and Geomagic Control X. CloudCompare is completely adapted to huge point-cloud processing with smart algorithms and high efficiency levels in terms of big data processing based on a proprietary octree structure. MeshLab is designed to perform elaborate mesh processing using the GPL VCG library. Generally, MeshLab and CloudCompare each carry specific estimates of their strengths and weaknesses.

2.4. Factor: different level of clinical scanning experience

Research has indicated that the level of scanning experience can affect the accuracy of digital impressions [34,35] and design outcomes using CAD programs [36]. Additionally, training significantly influences the scanning time required to increase the scanning accuracy [37]; however, some studies have concluded that digital scans produced by experienced operators do not exhibit greater accuracy than those produced by inexperienced operators. In fact, there are studies stating that scans from inexperienced operators demonstrate higher trueness and greater precision for edentulous maxillary model [38]. A key consideration in CAD/CAM research for assessing accuracy is the variability in the trueness of the IOS results based on the practitioner's experience. This may be linked to the specific scanning pattern tested, which can significantly affect trueness and precision values, as well as the scanning duration and the number of photograms used for the extraoral digitization of maxillary and mandibular complete dentures with the evaluated IOS [24]. To evaluate the level of clinical scanning experience, two approaches were used: (a) a trained clinician expert in CAD and prosthodontics with over 10 years of expertise in using IOS and more than 1500 CAD/CAM restorations, and (b) a dental student, a first-time user with no prior experience, who had performed 12 complete arch scans.

3. Statistical analysis

Statistical analyses were performed using SPSS ver. 29 (IBM Corp., Armonk, NY, USA) to estimate the differences in RMS values across multiple factors, including the scanner type, scanning pattern, user expertise, and number of alignment points. Three IOS (Omnicam, Primescan, and Trios 3) and two scanning patterns (Quatrad vs. Arch) were evaluated, along with two user groups (master vs. student) and four alignment point groups (4, 10, 20, and 30 points). The normality and homogeneity of variance of the RMS values were assessed using the Shapiro–Wilk and Levene's tests, respectively. Significant deviations from normality ($p < 0.05$) and violations of variance homogeneity ($p < 0.001$) informed the choice of statistical tests. Specifically:

1. Non-Parametric Tests:
   - The Kruskal–Wallis test was used to compare more than two independent groups when normality assumptions were violated.
   - Pairwise comparisons were conducted utilizing the Mann–Whitney *U* test, which is robust for non-normally distributed data.
2. ANOVA for Interaction Effects:
   - Welch's ANOVA was applied to analyze the differences between groups when the homogeneity of variance was violated, ensuring reliable results under these conditions.
   - Standard two-way ANOVA was employed to explore the interaction effects between scanner type and scanning pattern, as well as scanner type and user expertise, in cases where normality and homogeneity of variance were preserved.

3. Post-Hoc Tests:
   - Games–Howell post-hoc comparisons were performed in cases of unequal variances owing to their robustness.
   - Tukey's Honest Significant Difference test was used for pairwise comparisons when the variances were homogeneous.

Effect sizes were calculated using Partial Eta Squared to quantify the observed effects, and all statistical tests were conducted at an alpha level of $p < 0.05$. Adjustments for multiple comparisons were made using the Bonferroni method, and 95 % confidence intervals were reported to aid in the interpretation of the results. These tests were selected to address specific characteristics of the dataset, including violations of normality and variance homogeneity. These methods allowed for a comprehensive and reliable investigation of the factors influencing RMS accuracy under varying scanning conditions. Although alternative methods, such as generalized linear models, could have been used, the selected tests were deemed appropriate for the study's objectives and structure.

4. Results

The difference between the two meshes was determined using the RMS error metric. The mean values and standard deviations of the RMS for all IOS and various factors are presented in Table 1 and displayed in Figs. 1–6.

4.1. Factor: length of scanned area

Two-way ANOVA was used to investigate the influence of the three IOS (Omnicam, Primescan, and Trios 3) and two scanning patterns (Quatrad and Arch) on RMS values, which served as the measure of accuracy.

Scanning Pattern (Length): The Quatrad vs. Arch scanning pattern showed a significant difference in the RMS values [$F(1, 114) = 98.268$, $p < 0.001$, Partial Eta Squared = 0.463], which provided evidence that the type of pattern utilized in the process of scanning could affect the accuracy of the results. In response, scans using the arch pattern produced higher RMS values than those obtained utilizing the Quatrad pattern.

Interaction Effect: Highly significant interaction effect was observed between the scanner and scanning pattern; $F(2, 114) = 260.907$, $p < 0.001$, Partial Eta Squared = 0.821. This suggests that the effect of the scanner on the RMS value depends on the type of the pattern used. This implies that some of the scanners behaved differently depending on whether the Quatrad or Arch pattern was used.

Post-hoc Comparisons: Games–Howell post-hoc tests revealed the following significant differences between the scanners: Omnicam was significantly less accurate than Primescan ($p < 0.001$, mean difference = 0.23333) and Trios 3 ($p < 0.001$, mean difference = 0.19053). Similarly, Primescan and Trios 3 also showed a significant different at $p < 0.001$ (mean difference = 0.04280), with Trios 3 exhibiting slightly better accuracy.

Table 1
Performance metrics of each scanner under various examined factors.

Factor	Scanner Trueness		
	Omnicam	Primescan	Trios
	RMS Mean (mm) ± standard deviation		
Arch	0.525 ± 0.048	0.157 ± 0.017	0.149 ± 0.021
Quadrant	0.243 ± 0.054	0.145 ± 0.028	0.238 ± 0.039
MeshLab	0.525 ± 0.048	0.156 ± 0.018	0.149 ± 0.021
CloudCompare	0.492 ± 0.028	0.164 ± 0.014	0.184 ± 0.025
Geomagic Control X	0.243 ± 0.029	0.121 ± 0.012	0.093 ± 0.008
4-Points	0.519 ± 0.040	0.242 ± 0.018	0.202 ± 0.027
10-Points	0.528 ± 0.048	0.144 ± 0.010	0.195 ± 0.038
20-Points	0.525 ± 0.048	0.157 ± 0.017	0.149 ± 0.021
30-Points	0.524 ± 0.057	0.138 ± 0.024	0.177 ± 0.019
Student	0.121 ± 0.020	0.121 ± 0.013	0.146 ± 0.015
Expert	0.115 ± 0.005	0.129 ± 0.006	0.057 ± 0.013

4.2. Factor: total number of points of alignment

The Kruskal–Wallis test revealed a statistically significant difference in RMS values among the four alignment point groups (4, 10, 20, and 30 points), with $H = 18.739$, $df = 3$, and $p < 0.001$. Pairwise comparisons were conducted using the Mann–Whitney *U* test to determine the specific groups that were different.

- 4 points versus 30 points: The 4-point and 30-point groups showed a highly significant difference, with $U = 1115.500$, $Z = -3.593$, and $p < 0.001$, where the 4-point group had a significantly higher RMS value.
- 4 points vs. 20 points: There was also a highly significant difference between the 4-point and 20-point groups, with $U = 1056.500$, $Z = -3.903$, and $p < 0.001$, where the 4-point group had a significantly higher RMS value.
- 4 points vs. 10 points: Significant difference between the 4-and 10-point groups were noted, with $U = 1249.500$, $Z = -2.889$, and $p = 0.004$, where the 4-point group showed a higher RMS value.
- 10 points versus 30 points: The test did not show any significant difference in the RMS value between 10-point and 30-point groups, with $U = 1723.500$, $Z = -0.402$, and $p = 0.688$.
- 10 points versus 20 points: No significant difference was reported between 10-point and 20-point groups, with $U = 1665.500$, $Z = -0.706$, and $p = 0.480$.
- 20 points versus 30 points: No significant difference was noted between these groups, with $U = 1707.000$, $Z = -0.488$, and $p = 0.625$.

4.3. Factor: various software analysis program

Significant differences were observed between the 3D measurement programs. When comparing Meshlab and CloudCompare, the mean ranks were 54.89 and 65.03, respectively. The Mann–Whitney *U* test revealed no significant difference in accuracy between the two programs ($U = 1468.500$, $Z = -1.603$, $p = 0.109$), indicating their performances were equivalent. In contrast, when comparing Meshlab to Geomagic Control X, the mean ranks were 75.55 for Meshlab and 44.71 for Geomagic Control X. A significant difference was observed between the two ($U = 852.500$, $Z = -4.877$, $p < 0.001$), with Geomagic Control X showing significantly lower RMS values, indicating higher accuracy.

Finally, CloudCompare and Geomagic Control X had mean rank values of 77.53 and 43.48, respectively. The Mann–Whitney *U* test revealed a significant difference ($U = 778.500$, $Z = -5.362$, $p < 0.001$), further establishing Geomagic Control X as the most accurate.

4.4. Factor: different levels of clinical scanning experience

A significant main effect of user on RMS values was also found ($p < 0.001$). The master user exhibited significantly lower RMS values (0.057 ± 0.013) compared to the student user (0.121 ± 0.013), indicating that experienced generally produced more accurate scans, regardless of the scanner used.

Interaction Effects: Scanner × User.

A significant interaction effect between the scanner and user was identified ($p < 0.001$), suggesting that the performance of the scanner was related to the expertise of the user. For the Omnicam scanner, the student user exhibited higher RMS values (0.121 ± 0.020) than those of master user (0.115 ± 0.005). Whereas in the Primescan, slightly lower RMS values were recorded for the student user (0.121 ± 0.013) compared to those of the master user (0.129 ± 0.006). However, a significant difference was found between the RMS values obtained by the master and student users with the Trios 3 scanner, which were 0.057 ± 0.013 and 0.146 ± 0.013, respectively. This suggests that the

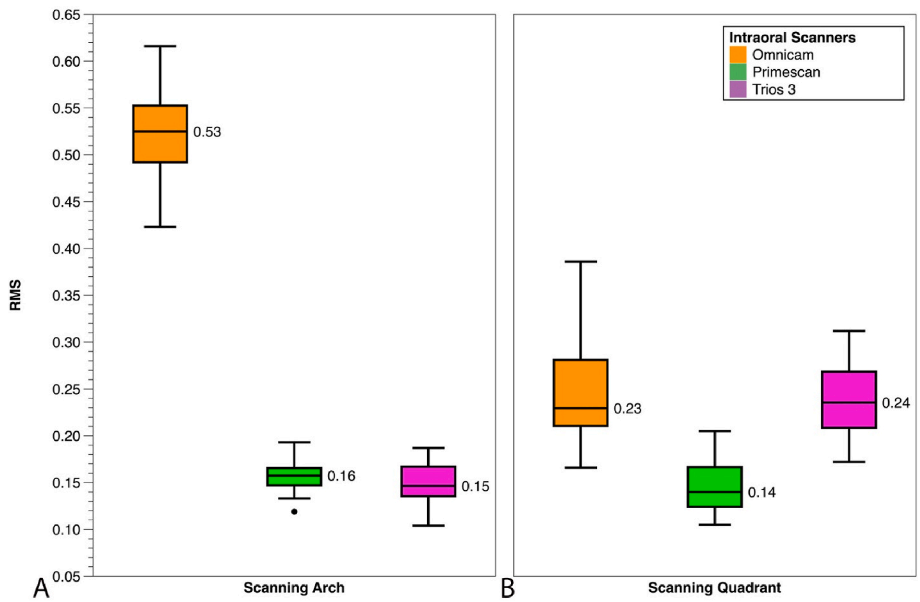

Fig. 1. RMS values for different scanning strategies using intraoral scanners. A) Arch scanning, B) Quadrant scanning.

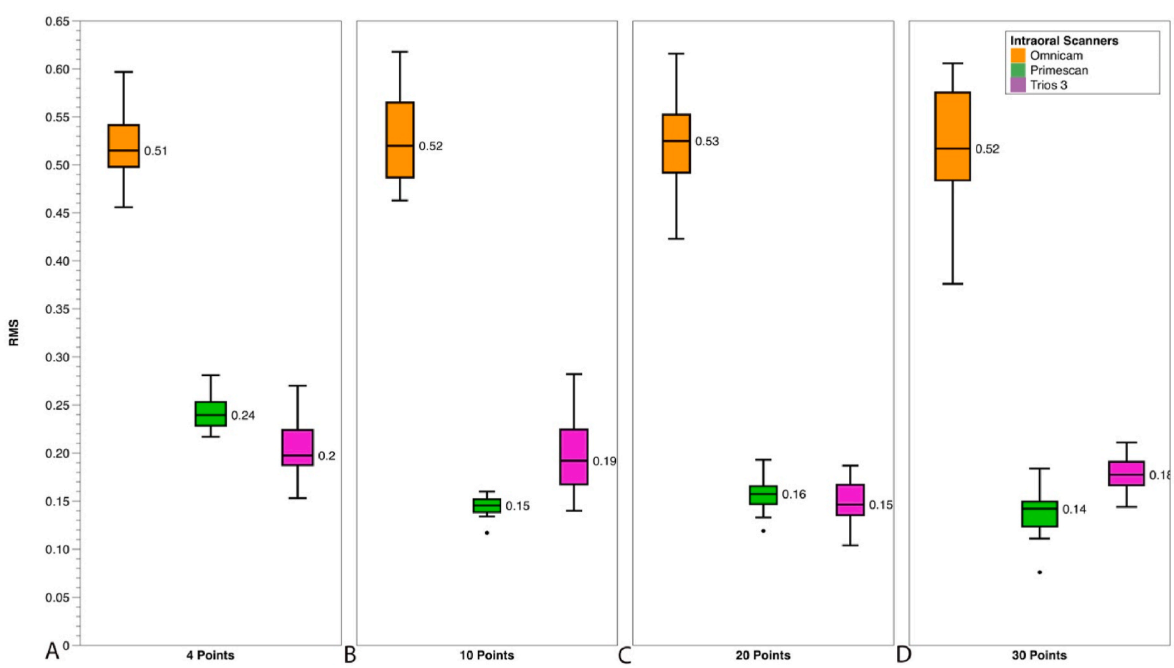

Fig. 2. RMS values using varying numbers of alignment points A) 4 alignment points, B) 10 alignment points, C) 20 alignment points, D) 30 alignment points.

performance of the Trios 3 scanner was highly sensitive to expertise, with significantly higher accuracy achieved by the master user.

5. Discussion

This study assessed several critical factors in the in vitro evaluation of IOS accuracy. These factors included the span length, alignment points used to compare the reference and examined scans, software used to calculate RMS values, and expertise of the IOS operator. Although this study evaluated the accuracy of three IOS and one desktop scanner, the selection was limited to commonly used devices representative of different scanning technologies. This approach ensures clinical relevance and practical applicability for most practitioners and researchers. However, the exclusion of newer or less common scanners is a limitation. Future studies should aim to incorporate a broader range of scanners to further validate the findings and explore whether advancements in technology influence the observed accuracy metrics. Expanding the scope to include innovative models could also provide insights into their potential for niche clinical applications such as full-arch or edentulous cases. Our findings revealed that the span of the scanned area played a crucial role in assessing the accuracy of digital impressions. Consequently, the first null hypothesis (Ho1) was rejected, and the alternative hypothesis, that the length of the scanned area influences RMS values, was accepted. These findings align with those of studies that evaluated the impact of scan length on the accuracy of dental scanners when used for digitizing prepared teeth [15] or evaluating the scanning distance on casts with implant abutments [39]. Research has predominantly investigated the effect of scanned area length by

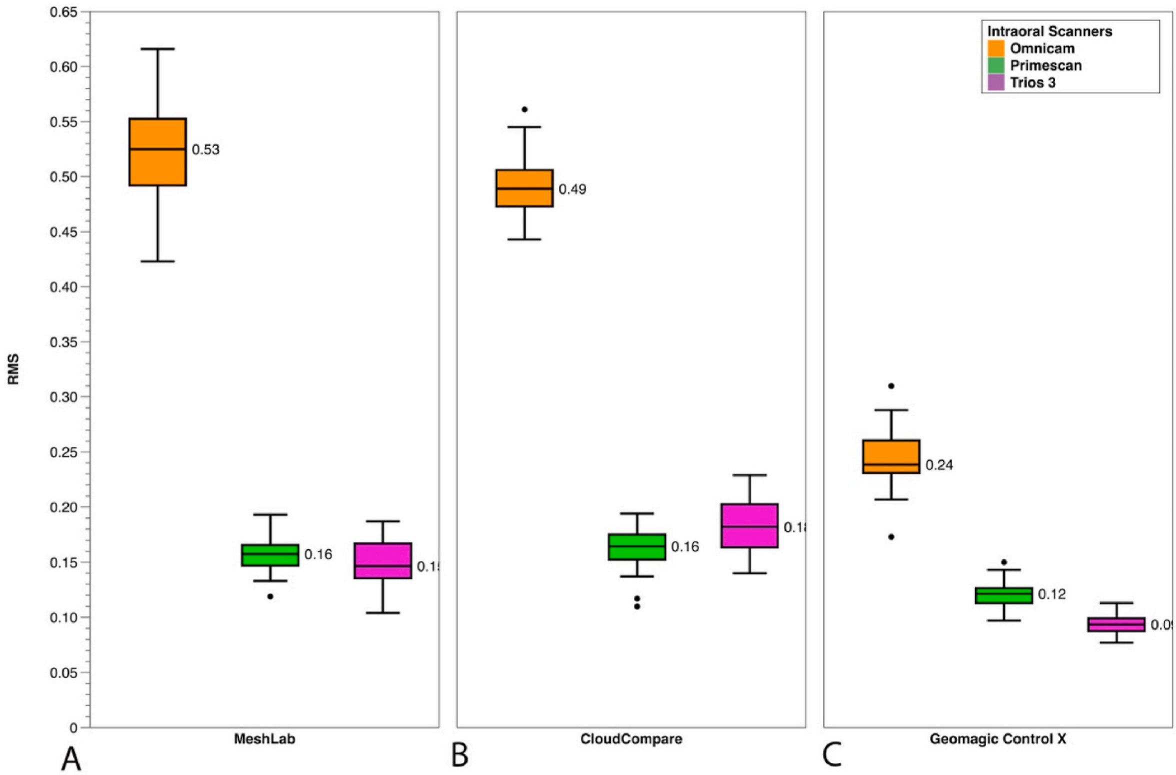

Fig. 3. RMS values using different software programs. A) Meshlab, B) CloudCompare, C) Geomagic Control X.

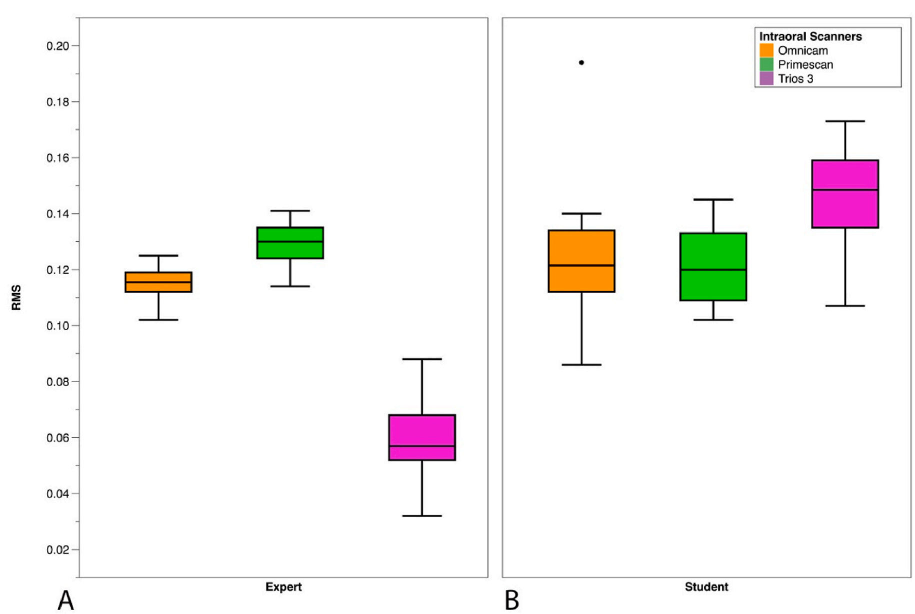

Fig. 4. RMS values using different intraoral scanners from different users. A) Expert, B) Student.

comparing the accuracy of IOS with that of desktop scanners for implant-supported complete arch fixed prostheses [40]. A key difference in evaluating scanner accuracy for implant-supported complete-arch fixed prostheses versus prepared teeth is the increased distance between the abutment and adjacent teeth, which impacts the accuracy [41]. In this study, both the factors (scanner type and scanning pattern) significantly influenced the accuracy of intraoral scans, as measured by the RMS value. Among all the scanners, Trios 3 was the most accurate, particularly when combined with the Quatrad pattern. The significant interaction effect suggests that each scanner exhibited unique performance based on its scanning pattern. Therefore, both variables played a relevant role in determining the scan accuracy. Scanning patterns, including starting point selection and sequence variation, play critical roles in the accuracy of intraoral scans, as highlighted in previous research [22,23]. These factors influence the completeness of data capture, stitching accuracy, and overall trueness of the scan. Although the current study utilized standardized protocols to minimize variability, future research should investigate how different scanning

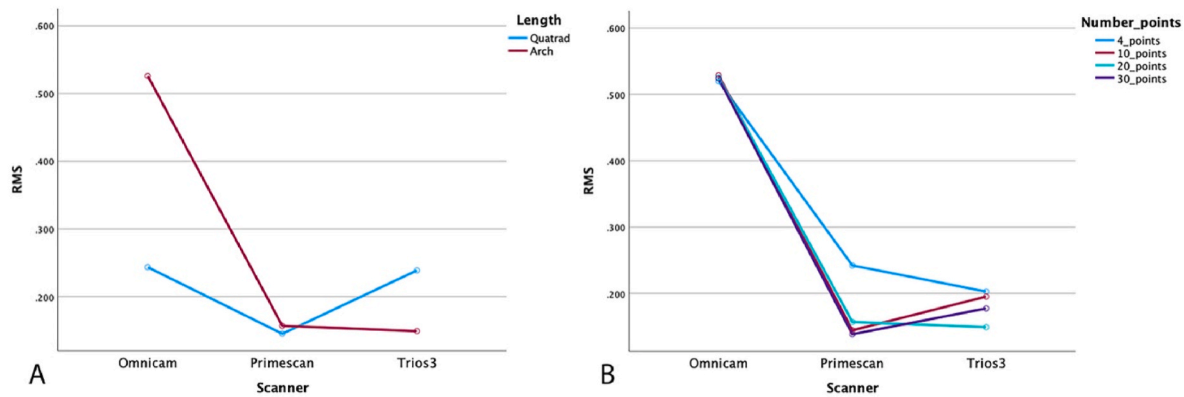

Fig. 5. Comparative Analysis of RMS Values Based on Scan Length and Alignment Points. (A) Comparison of RMS values based on the length of the scanned area. Full-arch scans (in red) show higher RMS values than quadrant scans (in blue), particularly for Omnicam and Trios 3, with Primescan demonstrating the lowest RMS values for both lengths. (B) RMS values compared based on the number of alignment points (4, 10, 20, and 30 points). A higher number of points corresponds to lower RMS values across all scanners. Trios 3 consistently demonstrates the lowest RMS values regardless of the number of alignment points. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

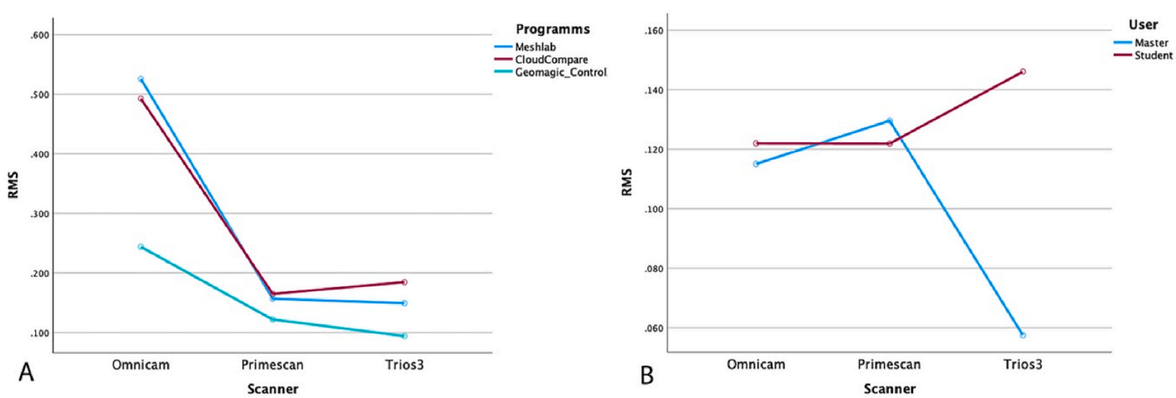

Fig. 6. Comparative Analysis of RMS Values Based on User Expertise and Software Programs (A) RMS values compared based on user expertise. Experienced users (in blue) generally achieve lower RMS values, especially with the Trios 3 scanner, which shows a significant reduction in RMS. Less-experienced users (in red) exhibit more consistent RMS values across the scanners, with minimal variance. (B) RMS values compared based on the software used for computation. Geomagic Control X (in cyan) demonstrates the lowest RMS values for Primescan, while CloudCompare (in red) and Meshlab (in blue) exhibit similar results across scanners. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

strategies affect accuracy metrics, particularly for complex geometries or full-arch cases. Incorporating a comparative analysis of diverse scanning techniques could provide a more comprehensive understanding of their impact on IOS performance and guide clinicians in optimizing their workflow.

Difficulties in data acquisition for large span lengths arise from poor reflection or high laser absorption. The complexity of image merging increases with the size of the scanned area, as the accuracy of IOS systems depends on the integration of individual images [42]. The larger the scanned area, the more complex is the merging process, making it difficult to integrate images accurately with the IOS system [43]. The level of alignment and stitching errors is thus related not only to the algorithms used but also to the quality of each individual image acquisition and the degree of image overlap [44]. Longer or more extensive scan paths exacerbate these errors, significantly affecting the overall scanning accuracy, particularly in complete arch scans [45].

This study also compared the alignment points used to match reference and test scans. These factors contribute to the calculation of RMS values, as greater superimposition accuracy corresponds to improved scanning precision of the IOS. Most studies pair a reference model with a test model, whereby the best fit is achieved using a best-fit algorithm. The models are then aligned, and the RMS value, a measure of accuracy, is calculated. This study demonstrated that a greater number of alignment points between two STL files allows the algorithm to fit the models more precisely, resulting in a lower RMS value. Thus, the second null hypothesis was rejected. This lower RMS value indicated a reduced discrepancy between the models. However, beyond a certain number of alignment points, further increases did not significantly affect the RMS values [46]. This phenomenon clarifies why expanding the number of alignment points from 10 to 20 or from 20 to 30 did not result in statistically significant differences in the study's outcomes. The findings suggest that the effect of increasing alignment points on RMS values became insignificant beyond a certain threshold, which may vary depending on factors such as scan length, scanner models, or the analysis software used. While this study examined a practical range of alignment points (4, 10, 20, and 30), future studies should investigate a wider range of alignment points under different experimental conditions to provide more complete guidance on achieving the best scanning accuracy.

To the best of our knowledge, only a limited number of studies have specifically evaluated the impact of alignment points on RMS values. Existing studies on the accuracy of IOS under various conditions typically do not specify the total number of alignment points used for the assessment of RMS values [40,47]. The results of this study align with the findings of Becker et al. [33], who found that the number of control points for reliable superimposition of the reference STL and

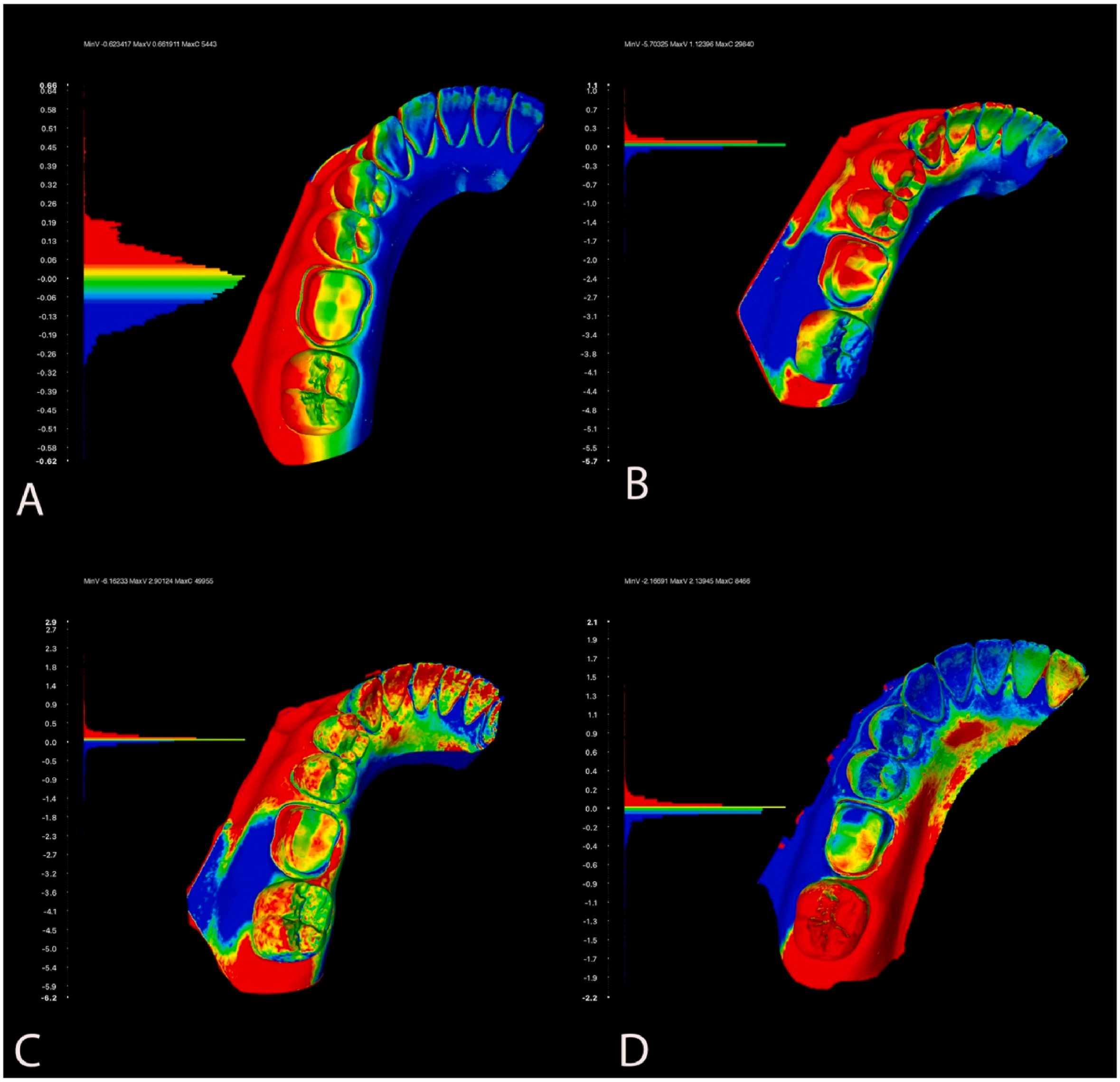

Fig. 7. Color map of RMS values for STL alignments comparing the reference STL (arch scan) and experimental STL (quadrant scan) using the same intraoral scanner. A) inEos X5, B) Primescan, C) Omnicam, D) Trios 3. Green and yellow regions signify minimal displacement within ±0.1 mm compared to the reference data. Red areas indicate significant outward displacements of +1.0 mm, and blue areas highlight substantial inward displacements of −1.0 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

experimental STL should exceed 10 carefully selected points. When 10 or more control points are utilized, the average alignment errors for both RMS errors and Hausdorff distances demonstrate convergence, indicating optimal registration performance [33]. One limitation of this study is the exclusive use of the RMS error as the primary accuracy metric without incorporating supplementary metrics, such as the Hausdorff distance or color deviation mapping. Although RMS error is widely accepted and consistently used in dental research, allowing for comparability with previous studies, it may not capture all aspects of scanner performance. For instance, the Hausdorff distance provides insights into the maximum deviation between two surfaces, which can complement RMS error by highlighting areas of significant discrepancy. The exclusion of this metric limits the scope of the study in providing a more holistic evaluation of IOS performance. The choice of accuracy metrics, such as the RMS error or Hausdorff Distance, depends on the specific aims of the study and the nature of the deviations being analyzed. RMS error provides an overall measure of deviations over the entire dataset and is well-suited for the computation of overall accuracy and systematic errors. By averaging all data points, RMS reduces the impact of outliers and the potential for biased results owing to particular reference points or planes, as it provides a consistent operator-independent analysis. This approach is advantageous for studies of distributed small-scale inaccuracies. However, Hausdorff Distance identifies the maximum deviation between two surfaces, capturing localized "worst-case" errors, which provides important information related to extreme tolerances. While the Hausdorff Distance is useful for identifying outliers and assessing peak discrepancies, RMS offers a global view of the cumulative accuracy within the dataset. Consequently, RMS was chosen because it directly compares scanning technologies and is an effective global measure of accuracy [48]. Nonetheless, future research should consider integrating the Hausdorff distance and other supplementary metrics to gain a broader understanding of scanner strengths and weaknesses in clinical and research applications. This study used advanced computational software such as Meshlab, CloudCompare, and Geomagic Control X to analyze IOS. While these tools employ complex algorithms to align and compare meshes, the methodological factors in dental research typically focus on issues that influence clinical outcomes than on the computational foundations

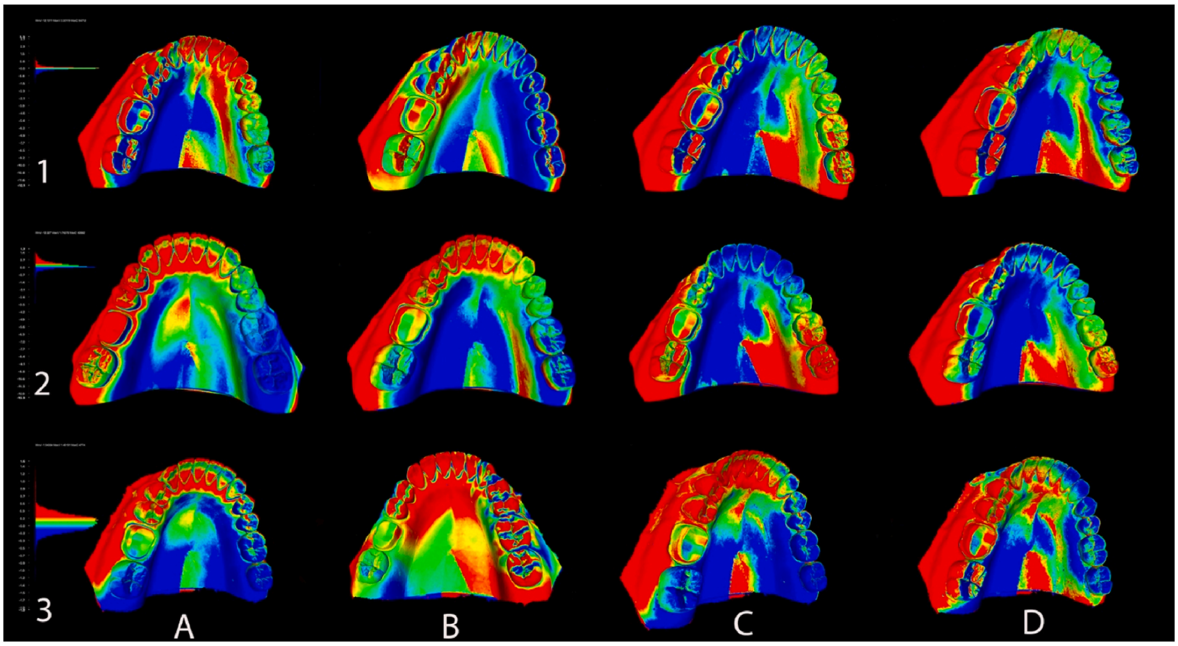

Fig. 8. Color map of RMS values for STL alignments using varying numbers of alignment points and different intraoral scanners. A) 4 alignment points, B) 10 alignment points, C) 20 alignment points, D) 30 alignment points. Intraoral scanners: 1) Omnicam, 2) Primescan, 3) Trios 3. Green and yellow regions signify minimal displacement within ±0.1 mm compared to the reference data. Red areas indicate significant outward displacements of +1.0 mm, and blue areas highlight substantial inward displacements of −1.0 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

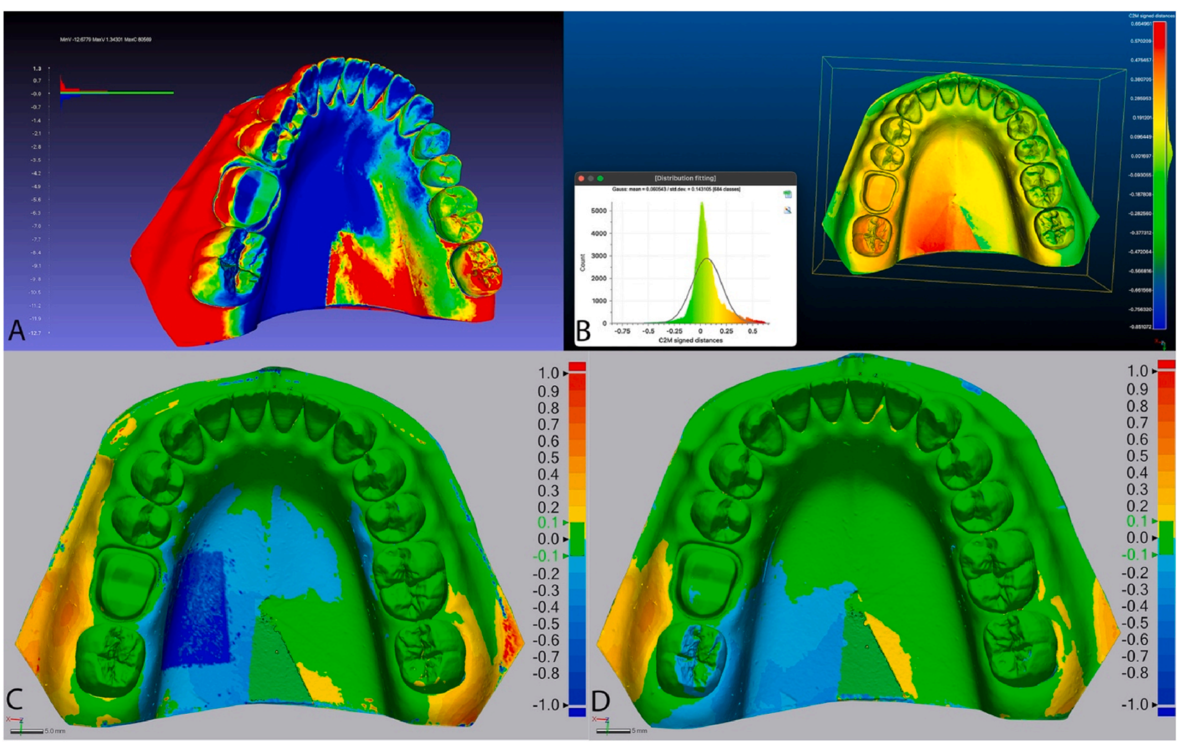

Fig. 9. Color map of RMS values comparing the same STL file acquired by the Primescan intraoral scanner using different software programs. A & C) MeshLab vs. Geomagic Control X. B & D) CloudCompare vs. Geomagic Control X. The color gradients represent surface deviations, with green indicating minimal deviation, while red and blue signify larger positive and negative discrepancies, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of these tools. Future research could attempt to address this gap by investigating the development of new algorithms or upgrading existing software to increase the efficiency of data processing workflows. Such advances may bring the convergence of computer science and dental research closer, fostering the development of methodological and computational intraoral scanning technologies.

Various software programs have been employed in research for analysis. For instance, MATLAB is a mathematical software system that calculates RMS values, though its interface can be challenging for users. However, in most studies, reverse-engineering software is commonly used, and the RMS values are computed over a superimposed reference STL file with experimental STL scans. Typically, these software programs provide color-mapped meshes between the discrepancies detected in each mesh. Generally, on the gradient scale, cooler colors represent negative deviations, warmer colors indicate positive deviations, and minimal deviations are depicted in green [46].

This study used CloudCompare version 2.13, an open-source software specially developed for processing 3D point clouds and meshes, and Meshlab version 2023.12, another open-source computer software used to process and edit 3D triangular meshes. Another similar software program, CloudCompare, was created to directly compare dense 3D point clouds. Its architecture is based on a handmade octree structure, which is generally known for its power and effectiveness in accomplishing special tasks [49]. All software used for STL superimposition and comparison employ specific alignment techniques, including 1) the best-fit algorithm, 2) reference-based best-fit or section-based best-fit, and 3) landmark-based best-fit alignment [11]. The landmark-based alignment technique is the default approach for alignment in most of the CAD software programs incorporated in this study. In this technique, the operator is required to manually select common landmarks or points on each scan, either the reference or the experiment, and use these to superimpose the scans. Subsequently, the application of the ICP algorithm can further improve the superimposition accuracy. It minimizes the distances between the corresponding points of the two datasets and thus can provide a more accurate fit result. The method applied in MeshLab and CloudCompare for aligning 3D models and point clouds is the Iterative Closest Point algorithm. MeshLab provides ICP to refine the initial alignment by minimizing the distance between the corresponding points. CloudCompare offers a robust implementation of the ICP algorithm for aligning dense 3D point clouds and meshes, with adjustable parameters to achieve optimal alignment results. Similarly, Geomagic Control X primarily uses an automated best-fit algorithm ICP for precise alignment and registration of 3D scans and CAD models, ensuring accurate measurements and comparisons [50]. The RMS values may be influenced by the software used because different programs implement varying alignment algorithms and deviation measurement methods. Misalignments and stitching errors are likely due to the algorithm used, but they can also be influenced by the quality of individual image acquisition and the extent of overlapping image areas, which, according to previous studies, substantially affect accuracy [10]. In this study, a 3D comparison was performed in both programs after aligning the reference and experimental STL files. During this comparison, the absolute mean distance between corresponding points was calculated using the RMS method. In particular, a low RMS value indicates excellent 3D matching of the superimposed data, corresponding to high trueness [51].

The study results showed a statistically significant difference among the three software programs, indicating that the RMS values were influenced by the measurement software [10,27,51]. Thus, the third null hypothesis was accepted. Specifically, the RMS values calculated using Geomagic Control X were significantly lower and more accurate than those calculated with Meshlab and CloudCompare, with Meshlab and CloudCompare showing similar accuracy. These findings contrast with those of a few studies that found inspection software has no impact on the trueness of the outcome [10]. However, those studies evaluated software programs different from those used in this study [27,51].

As for the last factor examined—the user expertise—Trios 3 produced the best results, with the master user achieving notably low RMS values that were significantly lower than those of both Omnicam and Primescan. Overall, Omnicam was the least accurate when used by the student user, while Primescan demonstrated intermediate performance. There was a strong interaction between the scanner and user, indicating that Trios 3 benefited the most from user expertise; the master user consistently outperformed the student user. These findings confirm that, among the three scanners tested, Trios 3 was the most reliable in terms of accuracy, exhibiting smaller variance, especially for more experienced users, whereas the results from both Omnicam and Primescan showed greater variability depending on user experience. Notably, this study evaluated the influence of user experience on scanning accuracy by categorizing participants into two groups: students and experts. Although this dichotomous classification is effective and allows for an understanding of the general differences in operator proficiency, it overlooks the subtle differences in skills and training. Recent studies in this field have adopted similar methods, typically comparing experienced and inexperienced users [52] or classifying participants into low, medium, and high levels of experience [53]. Such definitions for classification are inevitably subjective, with a potential lack of understanding of what intermediate or specialized levels of training truly entail. Finally, the present study was conducted in a controlled laboratory setup to isolate and evaluate specific methodological factors affecting IOS accuracy. This approach ensures reproducibility and precision but does not account for clinical variables, such as patient movement and saliva, which are integral to real dental practice. Future research should adopt a more detailed classification system to better understand how varying levels of experience and training influence the intraoral scanning accuracy. Additionally, clinical variables that may affect scanning accuracy should be investigated in future studies to build upon and enhance the findings of this study.

6. Conclusions

This study highlighted the significant influence of methodological factors—including scan length, alignment points, software analysis, and operator expertise—on the accuracy of IOS. Our findings suggest that standardized assessment protocols are necessary, and further research on these factors is warranted to optimize clinical workflows. While this study used well-established computation tools, future studies must focus on new and more sophisticated algorithms and methodologies to enhance the performance and reliability of scanners. These insights will help improve digital workflows in dentistry and support better clinical outcomes along with informed technology adoption.

Ethics statement

This study was conducted in full compliance with ethical standards. As it is an in vitro study, it did not involve human participants or animals, and therefore, did not require ethical approval from an institutional review board. All methods and protocols were designed to ensure scientific integrity and transparency.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compbiomed.2025.109780.

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