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Accuracy of Scanning Endocrown Preparation

ABSTRACT
Literature lacked sufficient evidence on the accuracy of modern intraoral scanners (IOSs) in capturing Endocrown preparations. This study assessed and compared the precision and trueness of six IOSs in scanning Endocrown preparation. Methods: This in vitro study involved scanning five extracted human teeth with one molar tooth prepared for Endocrown restoration. A total of 36 scans were conducted, scans were compared, and the root mean square (RMS) values were calculated to assess precision and trueness (N=306). Descriptive and inferential non-parametric statistics were performed. Results: Statistical analysis revealed significant differences between IOSs ($p < 0.05$). One IOS exhibited the highest precision with a mean RMS value of 6.49 µm, but had the lowest trueness, with a mean value of 52.35 µm. The range of precision values across all IOSs was 6.49 µm to 16.65 µm, whereas trueness values ranged from 27.07 µm to 52.35 µm. Notably, the order of IOSs varied between precision and trueness assessments. Conclusion: Clinicians are required to weigh both accuracy parameters, trueness and precision. Primescan demonstrated superior precision but lagged in trueness, whereas Aoralscan 3 had the highest trueness but the lowest precision. Aoralscan Elite and TRIOS 5 demonstrated both strong precision and trueness.

INTRODUCTION
Intraoral scanning has revolutionized digital dentistry by offering a reliable alternative to conventional impression techniques. Traditional impression methods, while widely used, have notable disadvantages, such as patient discomfort due to the physical characteristics, taste, and odor of impression materials. These factors often lead to suboptimal patient experiences and treatment compliance.[1, 2] In contrast, intraoral scanners (IOSs) provide digital, three-dimensional (3D) capture of dental structures, allowing for enhanced accuracy, reduced chair time, and increased patient satisfaction.[3-5] With the advancement in computer-aided design/computer-aided manufacturing (CAD/CAM) technology, IOS has become integral to a fully digital workflow, enabling precise and efficient fabrication of dental prostheses.[6-9]
Endocrowns are a minimally invasive restorative option for endodontically treated teeth, prioritizing the preservation of natural tooth structure. Compared to traditional crowns, which often necessitate extensive tooth preparation and the placement of posts for retention, Endocrowns rely on the pulp chamber and surrounding walls for mechanical stability.[10] This approach minimizes procedural complexity, reduces treatment time, and helps maintain the tooth's structural integrity, offering improved biomechanical performance and aesthetics.[11, 12] Furthermore, the use of adhesive bonding techniques with Endocrowns enhances their retention and strength, making them a reliable choice for restoring structurally compromised teeth.[13]
The success of Endocrowns is further enhanced by advancements in digital fabrication methods, particularly CAD/CAM technology, which ensures high precision and efficiency in their production. One study demonstrated excellent marginal and internal fit using CAD/CAM systems, ensuring durability even with varying cavity depths.[14] Moreover, two studies underscored the superior fit and performance of lithium disilicate and PEEK CAD/CAM materials for Endocrowns.[15, 16] Additionally, It was confirmed that milling-based digital techniques outperform conventional methods like heat pressing in achieving superior marginal and internal fit.[17] However, despite the precision offered by CAD/CAM technology, challenges persist in accurately scanning Endocrowns

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using IOSs, largely due to their complex geometry and reliance on both the pulp chamber and peripheral walls for stability.[18]

The depth and morphology of the pulp chamber significantly impact the scanning accuracy, with studies indicating that deeper chambers can reduce the trueness and precision of digital impressions.[18, 19] In a related study, the authors evaluated the accuracy of direct IOS impressions for digital post and core restorations of varying post lengths, highlighting the challenges associated with scanning deep and narrow preparations. Their findings reinforce the notion that IOS accuracy is highly dependent on preparation depth and configuration, which is particularly relevant to the scanning of Endocrowns.[20] Moreover, the presence of adjacent teeth and intricate marginal designs can hinder IOS performance, it was found that neighboring anatomical structures compromise the scanner's ability to capture Class II inlay preparations accurately.[21] Endocrown scanning is also complicated by variability in the accuracy of scanners of various types of preparations, with specific IOSs having problems with reproducible results in intracoronal restorations.[22] Additionally, the localized accuracy of IOSs at critical intaglio and marginal surfaces is crucial for ensuring proper fit but remains a persistent limitation.[23, 24] These factors highlight the need for advanced scanning technologies and refined protocols to optimize the digital workflow for Endocrown fabrication.

IOSs are evaluated for their accuracy based on two fundamental parameters: precision and trueness, as defined by the International Organization for Standardization (ISO 5725). Precision refers to the degree of reproducibility among repeated measurements, reflecting the scanner's ability to consistently capture identical data across multiple scans. Trueness, on the other hand, measures the closeness of the mean value of multiple scans to the actual reference standard, indicating how accurately the IOS replicates the true morphology of the scanned object.[25] Numerous studies have investigated the accuracy of various IOSs; however, their findings remain inconclusive due to significant discrepancies in study methodologies, scanning protocols, sample types, and evaluation criteria. The lack of standardization across studies has led to inconsistent results, making it challenging to draw definitive conclusions regarding the comparative accuracy of different IOS systems.[26-28]

The objective of this in vitro study is to evaluate the precision and trueness of six distinct IOSs in capturing scans of extracted natural human teeth prepared for Endocrown restorations. By employing 3D comparisons of the generated scans, root mean square (RMS) values will be analyzed to identify which IOS achieves the highest accuracy in scanning Endocrown preparations. The study's null hypotheses assert that (1) no significant differences exist in the precision of scanning Endocrown preparations among the six IOS groups (H_{0i}) and (2) no significant differences exist in the trueness of scanning Endocrown preparations among the six IOS groups (H_{0ii}). However, considering the inherent variability in scanning technologies, the findings may reveal significant disparities, potentially influencing clinical decision-making in restorative dentistry.

MATERIALS AND METHODS

This in vitro study aimed to evaluate the precision and trueness of different IOSs when scanning extracted natural teeth with Endocrown preparations. The study was conducted following ethical approval from the institutional review board (IRB number: SCBR-264/2024).

Teeth Model Preparation

Five extracted human mandibular teeth were collected from the dental clinic of Prince Sattam bin Abdulaziz University. These teeth were embedded in Type III dental stone (Elite Model, Elite Dental Stones, Zhermack, Badia Polesine, Italy) to create a stable base for Endocrown preparation and subsequent scanning. The Endocrown cavity was prepared on one bounded molar tooth while ensuring a 2 mm occlusal reduction and a 5 mm internal depth based on the designs described in the literature.[29, 30] The remaining teeth were left intact. The use of natural teeth provided a clinically relevant representation, as surface materials have been shown to influence IOS accuracy.[31, 32]

Intraoral and Reference Scans

For this study, six commercially available IOSs were selected: Aoralscan 3 (Shining 3D, Hangzhou, China), Aoralscan Elite (Shining 3D, Hangzhou, China), iTero Element 5D Plus (Align Technology, San Jose, CA, USA), Primescan (Dentsply Sirona, Charlotte, NC, USA), TRIOS 4 (3Shape A/S, Copenhagen, Denmark), and TRIOS 5 (3Shape A/S, Copenhagen, Denmark). To minimize variability, all scans were conducted by a single experienced operator. Each IOS system was used to perform six scans, resulting in a total of 36 scans. The scans were saved in the Standard Tessellation Language (STL) file format.

A laboratory reference scanner, E4 (3Shape A/S, Copenhagen, Denmark), was selected for trueness evaluation. Since test conditions may influence the accuracy of the reference scanner, precision evaluation is essential to confirm its suitability.[25] To validate the reference scanner, the teeth model was scanned six times to assess precision. The six reference scans were then saved in STL file format.

Scan Data Trimming and 3D Comparison

The scan files were imported into 3D modeling and editing software (Meshmixer software, version 3.5.474, Autodesk Inc., San Francisco, CA, USA) for scan data trimming, isolating only the Endocrown tooth preparation (pulp chamber and margins) to exclude irrelevant scan data. Figure 1 shows 3D scan of the teeth model and isolated Endocrown preparation. The trimmed scans were then transferred to 3D inspection and metrology software (Geomagic® Control X 2018;

3D Systems, Rock Hill, SC, USA) for 3D comparisons. For precision evaluation, all six scans within each IOS group were analyzed through pairwise 3D comparisons, resulting in 15 comparisons per IOS group (N=90). For trueness evaluation, the six scans within each IOS group were individually 3D compared against the six reference scans, generating 36 comparisons per IOS group (N=216). Each 3D comparison yielded RMS value, quantifying the deviations between scans to assess both precision and trueness. For validation of reference scanner, the six reference scans were compared as well in pairs (15 comparisons) and an acceptable precision was obtained (mean RMS=6.61µm).

Figure 1. Top: 3D scan of the teeth model. Bottom: A trimmed Endocrown preparation.

Calculating Root Mean Square Values

For each 3D comparison, the software determined deviation values for the vertices in the second scan data. Each test vertex, defined by its position (P_s), is associated with a reference first position (P_f), which is determined based on the shortest projection direction.

$$P_s = \langle x_s, y_s, z_s \rangle,\ P_r = \langle x_f, y_f, z_f \rangle$$

For every test point, the software computed a gap vector (GV)-a vector originating at (P_f) and pointing toward (P_s).

$$GV = \langle x_s - x_f, y_s - y_f, z_s - z_f \rangle$$

This gap vector was then converted into a scalar value, referred to as the gap distance or deviation. The gap distance represents the deviation at a specific point, with a negative value assigned when the test point lies on the negative side of the reference data.

$$D = \sqrt{{GV_x}^2 + {GV_y}^2 + {GV_z}^2}$$

The average deviation (A) is calculated as the arithmetic mean of all gap distances, with (n) representing the total number of points in the 3D comparison.

$$A = \frac{1}{n}\sum_{i=1}^{n} D_i$$

To account for the influence of direction and focus solely on the magnitude of deviations, the *RMS*, a measure of the overall magnitude of deviations irrespective of direction, was calculated.

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {D_i}^2}$$

Statistical Analysis

Descriptive and inferential non-parametric statistical analyses were performed using SPSS Statistical software (version 24, IBM Corp., Armonk, NY, USA). Precision and trueness results were reported as mean RMS values, standard deviations (SD), and median RMS values for each IOS group. As the RMS value is the root of a squared value, i.e., a transformed value, a normal distribution of data was not assumed. Hence, the Kruskal-Wallis test was used to determine if significant differences existed between the six IOS groups. Pairwise comparisons were conducted with the Bonferroni correction to adjust for multiple comparisons (α = 0.05).

RESULTS

The precision and trueness of the six IOSs were evaluated based on their RMS values. Precision results showed noticeable variation among scanners, with some demonstrating significantly lower mean RMS values, indicating higher repeatability. In contrast, trueness rankings differed from precision, with certain scanners exhibiting lower deviations from the reference standard. Overall, all scanners performed within clinically acceptable limits. Full descriptive statistics, including mean, standard deviation, and median values, are presented in Table 1.

Table 1. Mean, standard deviation (SD) and median values for the root mean square (RMS) values (µm) for the precision and trueness of the intraoral scanners (IOSs).

Precision			Trueness		
Group	**Mean (SD)**	**Median**	**Group**	**Mean (SD)**	**Median**
Aoralscan 3	16.15 (7.27)	13.81	**Aoralscan 3**	27.07 (4.52)	25.98
Aoralscan Elite	8.67 (1.59)	8.22	**Aoralscan Elite**	35.11 (5.28)	35.31
iTero Plus	15.15 (11)	10.68	**iTero Plus**	47.31 (13.26)	45.16
Primescan	6.49 (1.88)	5.76	**Primescan**	52.35 (10.81)	53.63
TRIOS 4	16.65 (4.64)	15.37	**TRIOS 4**	49.57 (9.32)	50.3
TRIOS 5	10.48 (2.28)	9.89	**TRIOS 5**	32.92 (3.52)	32.94

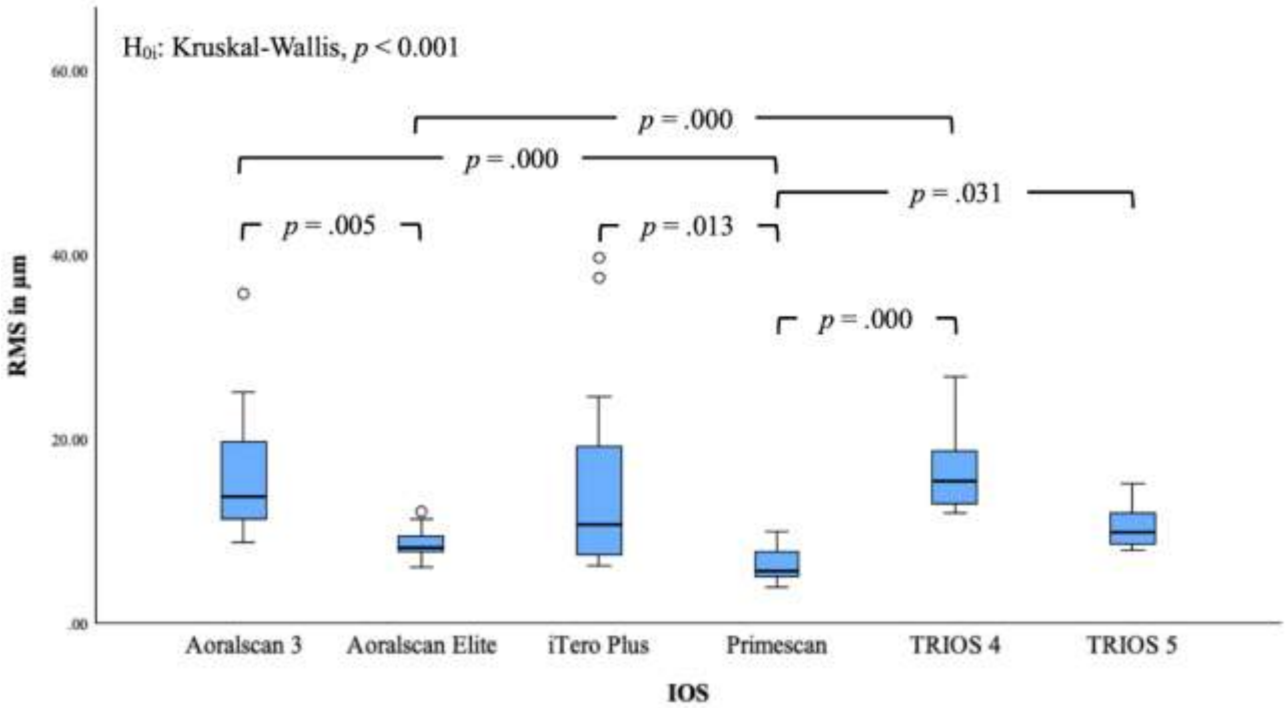

Figure 2. Boxplot of the IOS groups used to test the first null hypothesis for precision evaluation. Statistically significant nonparametric test statistics (α=.05) are displayed.

The Kruskal-Wallis test for precision confirmed significant differences among the six IOS groups ($p < 0.001$), leading to the rejection of the null hypothesis (H_{0i}). Pairwise comparisons indicated that Primescan had the highest precision, demonstrating significantly superior repeatability compared to Aoralscan 3, TRIOS 4, iTero Plus, and TRIOS 5 ($p < 0.05$). Aoralscan Elite ranked as the second most precise scanner, showing significantly higher precision than Aoralscan 3 and TRIOS 4 ($p < 0.05$). TRIOS 4 demonstrated the lowest precision, with no significant difference compared to Aoralscan 3, iTero Plus and TRIOS 5, confirming their lower repeatability. Figure 2 is a boxplot of the groups used to test the IOSs precision.

Similarly, the Kruskal-Wallis test for trueness also showed significant differences among the IOS groups ($p < 0.001$), leading to the rejection of the null hypothesis (H_{0ii}). Aoralscan 3 exhibited the highest trueness, significantly outperforming all other scanners ($p < 0.05$), making it the most accurate in representing the reference standard. TRIOS 5 ranked as the second most accurate scanner, demonstrating significantly superior trueness compared to Primescan and TRIOS 4 ($p < 0.05$). Primescan recorded the lowest trueness, with no significant differences were found when compared to iTero Plus or TRIOS 4 ($p = 1.000$), suggesting similarly lower accuracy among these scanners. Figure 3 is a boxplot of the groups used to test the IOSs trueness.

DISCUSSION

Precision refers to the repeatability of an IOS when capturing the same object multiple times. Our findings revealed statistically significant differences among the six IOSs with Primescan demonstrating the highest precision (6.49 ± 1.88 µm) and TRIOS 4 the lowest (16.65 ± 4.64 µm). These findings align with previous research where Primescan outperformed other IOSs in terms of repeatability.[26] Interestingly, the newer models such as, Aoralscan Elite (8.67 ± 1.59 µm) and TRIOS 5 (10.48 ± 2.28 µm), demonstrated precision levels comparable to Primescan. This suggests that recent advancements in scanning technology are reducing performance discrepancies among IOSs, making newer models increasingly competitive in terms of repeatability.

Trueness assesses how closely a scan matches the actual dimensions of a reference standard. In this study, Aoralscan 3 demonstrated the highest trueness (27.07 ± 4.52 µm), while Primescan had the lowest (52.35 ± 10.81 µm), with statistically significant differences among the IOS groups. Interstingly, trueness findings contrast with precision rankings. Primescan, despite having the best precision, exhibited the lowest trueness, a trend also noted in prior research, where high precision does not always equate to high trueness.[27, 28] This discrepancy might be due to the aggressive image processing algorithms in Primescan, which enhance repeatability but introduce minor distortions when compared to a reference model. Conversely, Aoralscan 3, while less precise, was the most accurate in representing true surface details, possibly due to its optimized depth-scanning capabilities. Newer IOSs like Aoralscan Elite and TRIOS 5 exhibited trueness values (35.11 ± 5.28 µm and 32.92 ± 3.52 µm, respectively) that were superior to Primescan, iTero Plus, and TRIOS 4, further highlighting that newer models may offer a more balanced performance.

A key consideration in IOS performance is the relationship between precision and trueness. The results of this study suggest that an IOS that excels in precision

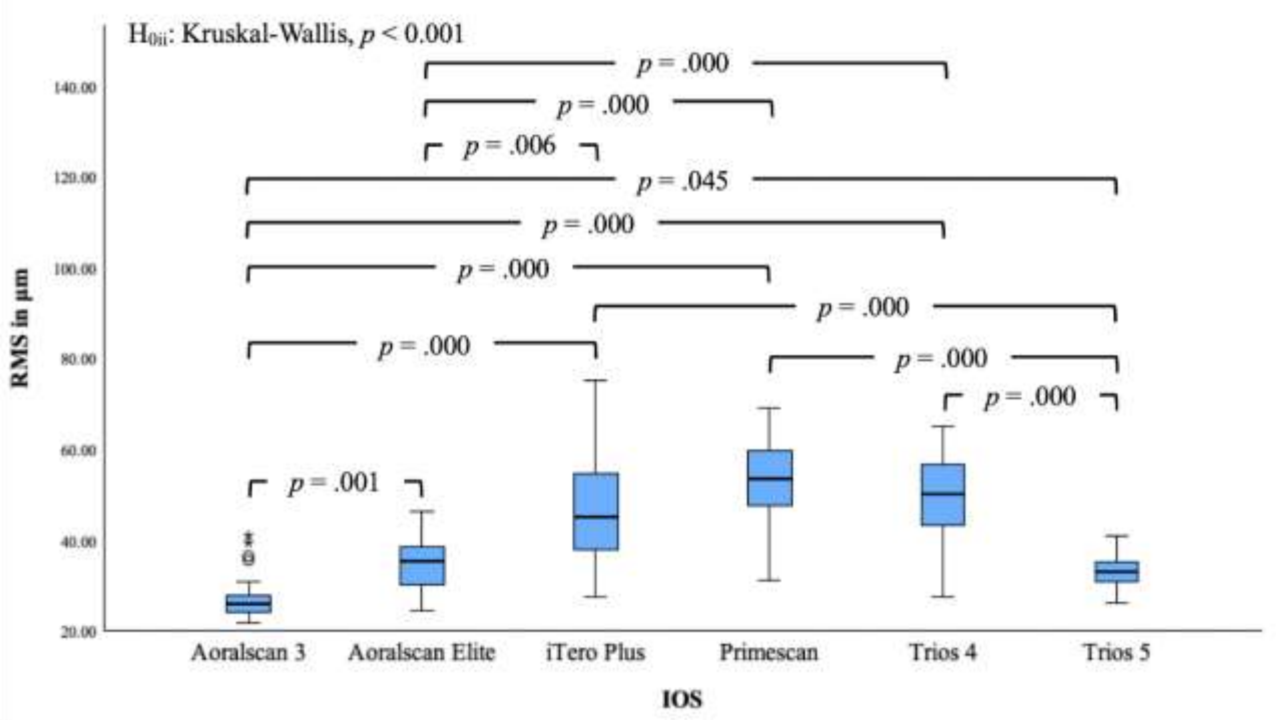

Figure 3. Boxplot of the IOS groups used to test the second null hypothesis for trueness evaluation. Statistically significant nonparametric test statistics (α=.05) are displayed.

does not necessarily have superior trueness, and vice versa. This trade-off is critical when choosing a scanner for clinical use. Primescan, for example, offers excellent repeatability but introduces deviations from the actual surface details, whereas Aoralscan 3 produces highly accurate representations but lacks consistency across repeated scans. This difference between scans is clearly illustrated by the wireframe overlying the 3D scans of different IOS groups where some have a more simplified wireframe, with larger polygons and fewer divisions suggesting a lower-resolution mesh compared to others with denser wireframe, more subdivisions and smaller polygons indicating a higher-resolution mesh (Figure 4).

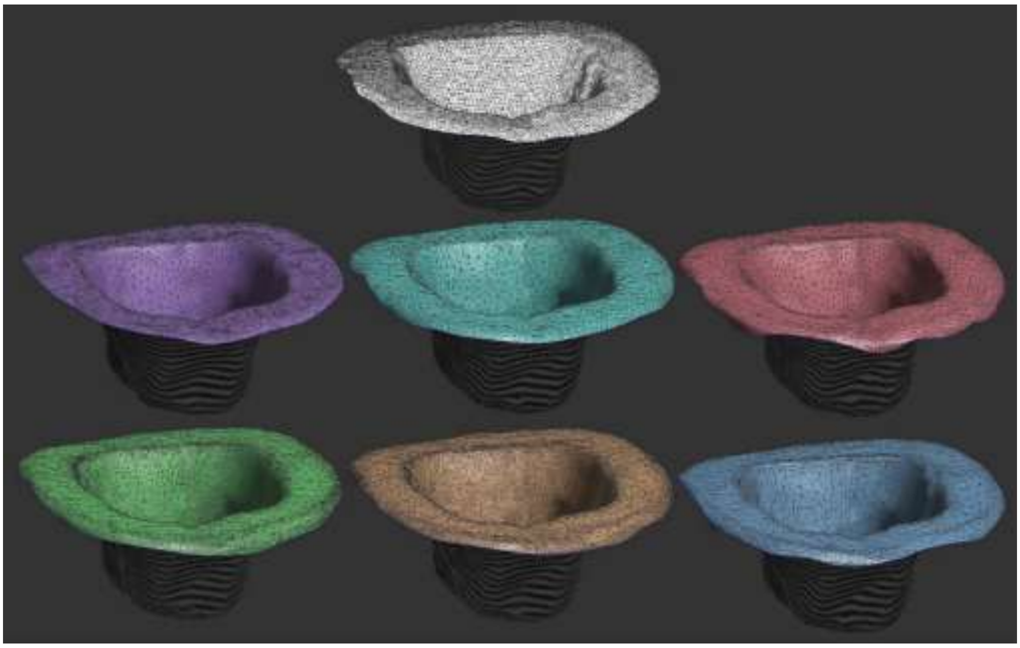

Figure 4. Representative wireframes for the different IOS groups and reference scans. White: reference scanner, Purple: Aoralscan 3, Teal: iTero Plus, Red: TRIOS 4, Green: Aoralscan Elite, Brown: Primescan, Blue: TRIOS 5.

Clinically, a scanner with both high precision and trueness is preferable over one that excels in only one of these parameters. Aoralscan Elite and TRIOS 5 emerge as balanced choices, as they demonstrated both good precision (8.67 µm and 10.48 µm, respectively) and strong trueness (35.11 µm and 32.92 µm, respectively). This suggests that these newer models may offer optimal performance without significant trade-offs between accuracy and repeatability. The correlation between precision and trueness is essential in digital dentistry, as a scanner with poor trueness may lead to inaccurate restorations, even if it exhibits excellent repeatability. Conversely, a scanner with high trueness but poor precision may result in inconsistent marginal fits across multiple scans, making it less reliable for prosthodontic applications. Thus, striking a balance between these two factors is crucial for achieving clinically acceptable digital impressions.

This study was conducted in a controlled laboratory setting using extracted teeth, which does not fully replicate intraoral conditions. Factors such as patient movement, saliva, soft tissue interference, and intraoral humidity may influence scanner performance in real-world applications. Additionally, since only one molar tooth was prepared for Endocrown restoration, the findings cannot be generalized to other types of tooth preparations or full-arch scans. The absence of these clinical variables and the limited scope of the study restrict the generalizability of the results. Further in vivo research is necessary to validate these findings under real clinical conditions and across different tooth preparations.

CONCLUSIONS

Within the limitations of this current study, the study underscores the significance of considering both precision and trueness when selecting an IOS for Endocrown preparation scanning. While Primescan demonstrated superior precision, it lagged in trueness, whereas Aoralscan 3 had the highest trueness but the lowest precision. Newer IOSs like Aoralscan Elite and TRIOS 5 demonstrated both strong precision and trueness, making them viable alternatives.

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