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Evaluation of the accuracy of digital impressions with different scanning strategies: An in vitro study

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ABSTRACT

Objectives: To evaluate the effects of three different scanning strategies on the trueness and precision of optical impressions obtained with four intraoral scanners (IOSs).

Methods: The reference maxillary dental arch model was fabricated using Telio CAD, and the reference digital reference cast was obtained using a computer numerical control machine and an optical scanner (E4, 3Shape, Copenhagen, Denmark). Test scans were performed with four different IOSs (TRIOS3, MEDIT i700, CS 3600, and iTero Element 5D) by an experienced operator and three different scanning strategies (S1: manufacturer-recommended, S2: optimal per previous literature, and S3: experimental). The scan duration was recorded for each scan. All scans were converted to standard tessellation language format and imported into Geomagic Control X. The accuracy was measured by absolute deviation/distance between aligned surfaces. Data of trueness and precision of each IOS and scan duration were statistically compared using analysis of variance for repeated measures and Bonferroni post-hoc test ($p < .05$).

Results: No significant differences in trueness were found among strategies (S1: 9.98 μm, S2: 11.93 μm, S3: 8.84 μm; $p = .388$) in Trios 3 and iTero Element 5D (S1: 12.24 μm, S2: 11.53 μm, S3: 10.71 μm; $p = p = .279$). Scanning strategy S3 with MEDIT i700 achieved greater trueness (7.33 μm) than S2 (16.33 μm, $p < .05$), while no significant difference was noted between S1 (10.44 μm) and S3 ($p = .291$). S3 showed the highest trueness (16.28 μm) compared to S2 (24.05 μm) and S1 (24.78 μm, $p < .001$) for CS 3600, with no difference between S1 and S2 ($p = .457$). Trios 3 had higher precision with S2 (22.46 μm) than S3 (31.69 μm, $p < .05$), and no significant differences between S1 (25.67 μm) and S2/S3 ($p > .05$). MEDIT i700 with S3 (29.52 μm) was more precise than both S1 (39.52 μm) and S2 (46.24 μm) ($p < .001$) with no difference between the last two ($p = .302$). S2 yielded the highest precision (44.93 μm) compared to S3 (61.81 μm) and S1 (76.53 μm) ($p < .001$) for CS 3600, with S3 more precise than S1 ($p < .001$). Similarly, iTero Element 5D showed S2 as the most precise (30.19 μm) compared to S3 (42.80 μm) and S1 (44.45 μm) ($p < .05$), with no difference between S1 and S3 ($p = .472$). Scan durations were shorter for S3 and S1 compared to S2 in Trios 3 ($p < .001$), and S3 was faster than S1 and S2 for MEDIT i700 ($p < .001$). CS 3600 scans with S1 were quicker than S2 and S3 ($p < .001$). For iTero Element 5D, no significant differences were found between S1 and S3 ($p = .511$), but S2 was slower than both ($p < .001$).

Conclusions: Scanning strategies significantly affect the accuracy and scan duration of optical impressions. Specifically, S3 provided the best trueness with both the MEDIT i700 and the CS 3600 while the S2 strategy demonstrated the highest precision for most scanners. Overall, the S1 and S3 strategies resulted faster than S2 among the devices evaluated.

Clinical Significance: The results suggest that the experimental scan strategy may optimize the use of intraoral scanners in clinical practice, potentially leading to more accurate and time-efficient dental impressions.

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1. Introduction

The advent of intraoral scanners (IOSs) is associated with the advancement of the computer-aided design computer-aided manufacturing (CAD-CAM) system [1].

IOSs are supposed to accurately capture the images of dentogingival tissue surfaces, enabling the immediate evaluation of virtual casts [2]. According to the International Organization for Standardization (ISO), accuracy comprises both trueness and precision (ISO 5725–1) [3]. Trueness denotes the measurement deviations from the reference values, whereas precision represents the repeatability of measurements [4].

A scanner with high trueness indicates that the scanner delivers a result that is close to or equal to the effective dimensions of the scanned object, while a scanner with high precision will provide a more constant and repeatable scan [5].

Intraoral scanning has become an increasingly popular technique in various prosthetic applications. The study by Boeddinghaus et al. [6] compared the marginal fit of dental crowns based on three different intraoral digital and one conventional impression method. The results showed that intraoral scanning achieved a similar level of accuracy to conventional impressions. Another study [7] assessed the accuracy of six IOSs for single crown preparations concluding that it varied depending on the IOS and scanning sequence used.

The accuracy of IOSs is influenced by the presence of saliva [8] and blood [9], light scanning conditions [10], temperature [11], operator [11,12], software update and substrate [13], and scan strategy.

The effect of scan strategies on the accuracy of IOSs has been assessed in several studies [14–18]. For instance, Mennito et al. [18] examined six IOSs and five scan strategies and found that scan strategies influenced the trueness of full-arch scans; however, no effects were observed on the accuracy of sextant scans. Similarly, Latham et al. [19] evaluated full-arch maxillary digital scans using four IOSs and four scan strategies. Their study, based on digital scans of a stone cast, documented variations in precision and trueness among the investigated scan strategies.

Although manufacturers of IOSs recommend their own scanning strategy and numerous authors have proposed different scanning strategies, ascertaining the optimal strategy is challenging.

Stitching error is a critical factor influencing trueness and precision in optical impressions. The stitching error occurs at the interface of adjacent scan regions and can introduce discrepancies in the final virtual cast [20,21]. By considering this mechanism, along with other relevant factors, we proposed an experimental scan strategy ("Grow Up") with the aim of minimizing stitching error and optimizing overall accuracy. The strategy is divided in two phases ensuring a more precise arch's acquisition after that the first area (from the last distal molar to the contralateral canine) is scanned. The technique is more predictable in the midline region, which is an area susceptible to errors.

Thus, this in vitro study aimed to evaluate the effects of three full-arch scan strategies (S1: manufacturer-recommended; S2: optimal per previous literature; and S3: experimental) on the precision, trueness, and scan duration of scans obtained with four IOSs.

The null hypotheses were that no significant differences existed between different scanning strategies and between different IOSs in terms of accuracy. Another null hypothesis was that no significant differences existed in terms of scanning time.

2. Material and methods

2.1. Intraoral scanner systems

Four IOS systems were assessed: TRIOS 3 (3Shape, Copenhagen, Denmark; software: Case Management: 1.5.1.3, TRIOS: 1.17.2.4), MEDIT i700 (Medit, Seoul, South Korea; software: Medit i700, wireless, v.3.0.3), CS 3600 (Carestream Dental, Atlanta, USA; software: CS IO 3D acquisition software, v. 3.1.0), and iTero Element 5D (Align Technology, San Jose, USA; software: software iTero Element™ 5D Plus). A custom reference standard model of the maxillary dental arch was fabricated, as described in a previous study [22], by using a millable Telio CAD (Ivoclar Vivadent, Schaan, Liechtenstein) disc. Telio CAD is a polymethylmethacrylate selected due to its refractive index (RI) of 1.49, which has been shown to closely resemble that of dentin (1.54) and enamel (1.63), thereby simulating natural tooth structure [19,22,23].

The model was fabricated using a computer numerical control (CNC) machine (Renishaw, Wotton-under-Edge, UK) to ensure the dimensional stability of the material. The maxillary dental arch model included 14 dental elements, but the maxillary right and left canines and second molars were deliberately replaced by four cylinders that were milled and formed a quadrilateral arrangement.

2.2. Reference virtual cast

The reference virtual cast was obtained by using two devices: an optical scanner E4 (3Shape, Copenhagen, Denmark) [24] and a Coordinate Measuring Machine (CMM) Renishaw DS10 (Renishaw, Wotton-under-Edge, UK) [25,26]. The scanner was used to scan the complete arch and the CMM to scan the position of the cylinders. Subsequently, the CMM and EOS scans obtained by the two devices were overlaid at the level of the cylinders to create a virtual reference model.

Both the CMM and the E4 scanner are highly accurate devices, as evidenced by various studies in which they were used to generate virtual reference models [24-26]. The measurements of discrepancies were ultimately taken from the position of the cylinders, which are detected using the CMM, universally recognized as the best machine for digitizing their shape.

2.3. Scan strategies and procedures

Three scan strategies (S1, S2, and S3) were selected (Figs. 1, 2, 3): S1, the strategy recommended by the manufacturer specific and previously described for iTero Element 5D [26], TRIOS 3 [27], MEDIT i700 [28] and CS 3600 [29]; S2, most accurate scan strategies according to Latham et al. [19] and Son et al. [21]; S3: "Grow Up", an experimental strategy. The S2 and S3 strategies are explained in detail as follows:

- **S2:** This technique starts from most distal molar on the patient's left side at 45-degree angle and continues at that angle until contralateral first premolar is captured, then returns to starting molar at 90-degree lingual angle. Then, proceed to contralateral canine from the occlusal angle. User will rotate to facial at 45-degree angle back to start molar and then back to contralateral canine at 90-degree facial angle. Pattern is repeated with the start tooth set to the canine on the patient's left side.
- **S3:** This technique is divided into two stages. In the first stage, the scanning begins with occlusal scanning from the last distal molar, moving towards the canine, followed by buccal/palatal rotation on the incisors (the scanning extends up to the contralateral canine relative to the quadrant where the scanning started). Subsequently, the second phase of the scan begins, starting from the incisors' palatal surfaces, already acquired, to complete the scanning of the entire arch. The scanning head is oriented parallel to the occlusal margins of the incisors - horizontal orientation - with buccal/palatal rotations for each tooth pair, ensuring consistent involvement of the incisal margins in the transition between palatal and buccal surfaces [4]. This is then followed by palatal scanning of the same hemiarch to the last distal molar, with buccal scanning concluding with occlusal scanning on the canine. Throughout the scan, the tip was never inclined >45° to prevent discrepancies in accuracy of the scan area [4,30,31].

The scanning sequence was randomly generated (https://www.random.org/sequences/). The same expert operator performed the scans with each IOS to avoid operator bias, with 10 scans for each scan strategy [10] yielding a total of 120 scans for four IOSs and three scan strategies. The time for each scan was recorded using a digital chronometer Casio HS-80TW-1EF (Casio Computer Co. Ltd., Tokyo, Japan).

During all scan sessions, a constant temperature was maintained (24 °C) using a thermostat because this temperature is considered optimal for performing scans [11]. According to the recommendations of a previous study [10], ambient light was maintained at 1005 Lux by using a ceiling light. Illuminance was measured using a Sekonic l-478D Litemater Pro light meter (Sekonic, Tokyo, Japan). Humidity was maintained at a constant level of 50 % using a humidity control system (dehumidifier), following the recommendations for clinical scanning environments [32].

Each scanner was calibrated before beginning the experiment, according to manufacturer guidelines.

2.4. Data processing and statistical analysis

All IOS scans were converted to standard tessellation language files and trimmed by using the Exocad Rjieka 3.1 software (Align Technology, San Jose, USA) to exclude extra-anatomical areas, focusing only on discrepancies at the level of the teeth. All experimental scans and the reference model were imported into the metrology software Geomagic Control X (3D Systems, Rock Hill, USA).

Using the Initial Alignment and Best Fit Alignment functions of the Geomagic software, the models were overlaid for 3D comparisons. The 3D comparison function allowed the measurement of differences and color map creation of the results. The upper and lower limits for color mapping were 0.5 mm. The areas highlighted in dark blue indicated a negative or inward deviation, whereas the areas highlighted in darker red indicated a positive or outward deviation of the test models [19] (Fig. 4)

The outcomes of the study were to determine the effects of the three different scanning strategies by using the four IOSs on: a) the trueness and precision of optical impressions, and b) the scan duration. The mean of the deviations from the alignment of the test scan with the reference scan was used to calculate trueness. To calculate precision, the scans were overlaid with each other, performed with the same scanner and the same strategy. The discrepancy values obtained from the Geomagic software were transferred to a spreadsheet (Excel, Microsoft Corp. Redmond, USA) to calculate both the average and standard deviations. A sensitivity power analysis was performed to determine the minimum effect size that can be reliably detected. The analysis was performed with G*Power 3.1 (Heinrich Heine, Universität Düsseldorf, Dusseldorf, Germany). Data from the test were synthesized by using means and standard deviations across all scanners and strategies. The data collected were checked for normal distribution using Shapiro–Wilk test and homogeneity of variance by applying Mauchly's test of sphericity. Because the data were normally distributed and the variances homogenous, data of trueness and precision and scan duration were statistically analyzed using analysis of variance for repeated measures and Bonferroni post-hoc test (Prism 9.4; GraphPad Software, Inc., CA, USA), with the significance level established at $p < .05$).

3. Results

The trueness, precision, and scan duration of each scan strategy for each scanner are listed in Table 1.

With a sample size of 120 scans, a power of 0.80 and $\alpha = 0.05$, the present sample size was adequate to detect a minimum effect size of 0.25.

3.1. Trueness

No statistically significant differences were evident among different scanning strategies for Trios 3 ($p = .388$) and iTero Element 5D ($p = .279$).

S3 and S1 showed greater trueness than S2 with MEDIT i700 ($p < .001$ and $p < .05$, respectively). No statistically significant difference was observed between S1 and S3 ($p = .291$). S3 exhibited greater trueness than with S2 and S1 with CS 3600 ($p < .001$), with no significant difference between S1 and S2 ($p = .457$).

3.2. Precision

The scans obtained with S2 were more precise than with S3 for Trios 3 ($p < .05$), with no significant differences between scans obtained with S1 and S3 ($p = .084$) or S1 and S2 ($p = .233$). S3 were more precise than with S2 ($p < .001$) and S1 ($p < .05$) for MEDIT i700. No statistically significant difference was observed between S1 and S2 ($p = .302$).

The scans obtained with S2 were more precise than with S3 ($p < .001$) and S1 ($p < .001$) for CS 3600, whereas those with S3 were more precise than with S1 ($p < .001$).

Finally, the scans obtained with S2 were more precise than with S3 ($p < 0.05$) and S1 ($p < 0.001$) for iTero Element 5D, with no statistically

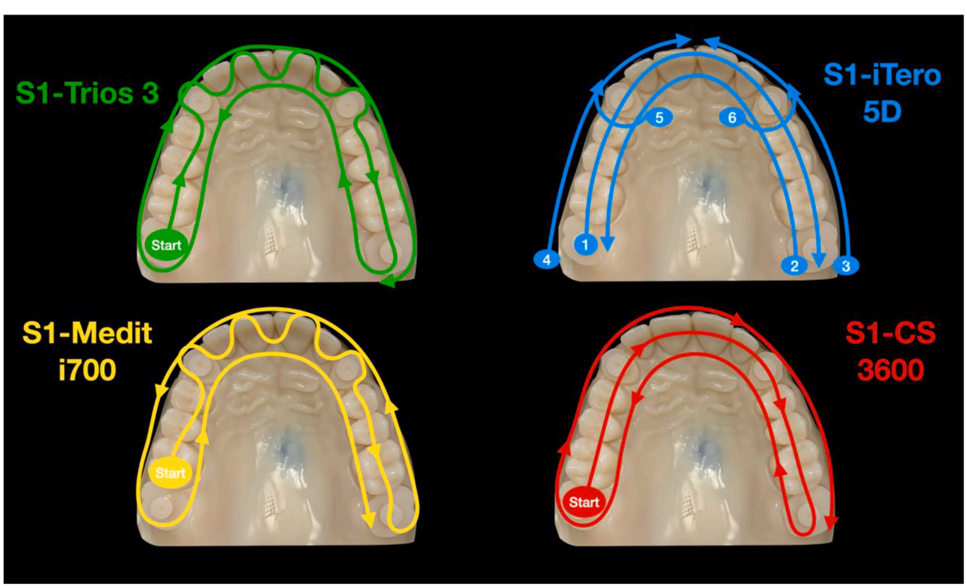

Fig. 1. S1 strategy as recommended by manufacturer for each IOS.

significant difference between scans obtained with S1 and S3 ($p = .472$).

3.3. Scan duration

The scan duration was smaller with S3 and S1 than with S2 for Trios 3 ($p < .001$). No significant difference was observed between S3 and S1 ($p = .421$).

The duration was significantly smaller with S3 than with S1 ($p < .05$) and S2 ($p < .001$) for MEDIT i700, with that for S1 being less than for S2 ($p = .001$).

The scan duration was smaller with S3 than with S2 ($p < .001$) for CS 3600, whereas that for S1 was less than for S2 and S3 ($p < .001$).

Finally, no statistically significant difference was observed between S1 and S3 ($p = .511$) for iTero Element 5D. The scan duration with S2 was greater than with S3 and S1 ($p < 0.001$).

4. Discussion

According to the results of this study, the first null hypothesis that scan strategies do not affect the trueness and precision of IOSs was rejected. Similarly, the second null hypothesis, that scan strategies do not affect the scan duration of scanners, was rejected.

The "Grow Up" scan strategy is based on several assumptions [33-35] that aim to optimize the effectiveness of the software and facilitate the scanning technique. The segmental scanning technique is comparable to continuous acquisition [16], assisting the operator in the correct positioning of the scanner. In terms of trueness, S3 was the best strategy for MEDIT i700 and CS 3600. For Trios 3 and iTero Element 5D, no statistically significant differences were found: the latest version of the corresponding software of the two scanners might render them less susceptible to the effects of scanning strategies on the final trueness of the optical impression.

The S2 allowed for more precise optical impressions with all devices except the MEDIT i700, for which S3 provided better results. CS 3600 was the most affected by the scanning strategy in terms of precision.

S2 had the greatest scan duration among those tested, which was probably related to the different scanning steps, making its clinical application difficult. Several studies have been conducted to evaluate the accuracy of optical impressions obtained with Trios3 [17-19]. This study reported no effect of scan strategy on the trueness of scans obtained with Trios3, as previously reported [19].

Previous studies did not include all the scanners analyzed in the current study; other studies investigated different models of the same scanner [25]. These methodological differences make it difficult to compare the current and previous study results.

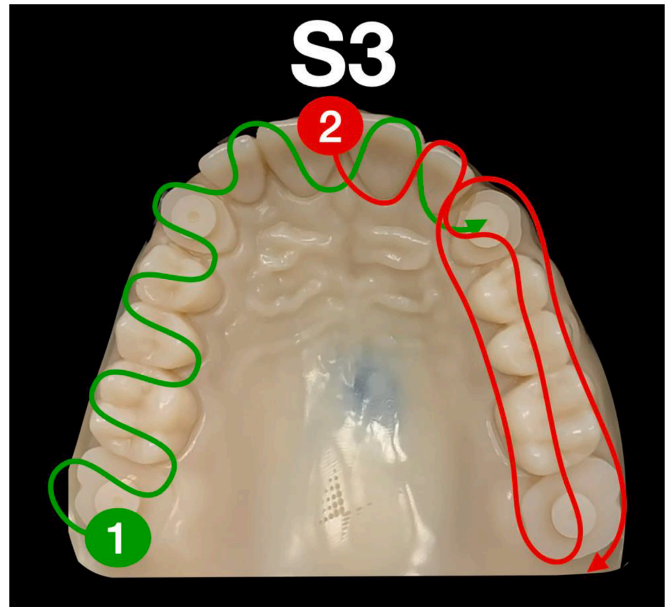

Fig. 3. S3 strategy is the experimental (Grow-up) technique.

A significant finding of this study is that MEDIT i700 should be used by applying S3 to obtain the best combination of speed, trueness, and precision.

Regarding the laboratory scanner's precision, we utilized the scanner in conjunction with a computer numerical control machine. Although the scanner has a trueness of 12 μm, the CNC machine compensated for the error, and we averaged the data from both devices. Thus, our model achieves a trueness better than 12 μm [24].

Concerning the clinical relevance of the observed differences, while the differences noted at this stage of our study may not be directly clinically relevant, we cannot extrapolate these findings directly to clinical outcomes. This is because our evaluation focused on a single phase of a multi-step digital workflow, where additional errors could arise, potentially affecting the clinical fitting.

This study has some limitations. Firstly, the in vitro design may not fully replicate clinical conditions, particularly the impact of saliva on the accuracy of digital scans. The model used in this study does not accurately represent the compressibility of intraoral tissues, which can cause differences in accuracy between conventional impressions and digital scans [36,37]. Additionally, we only evaluated four IOS systems with

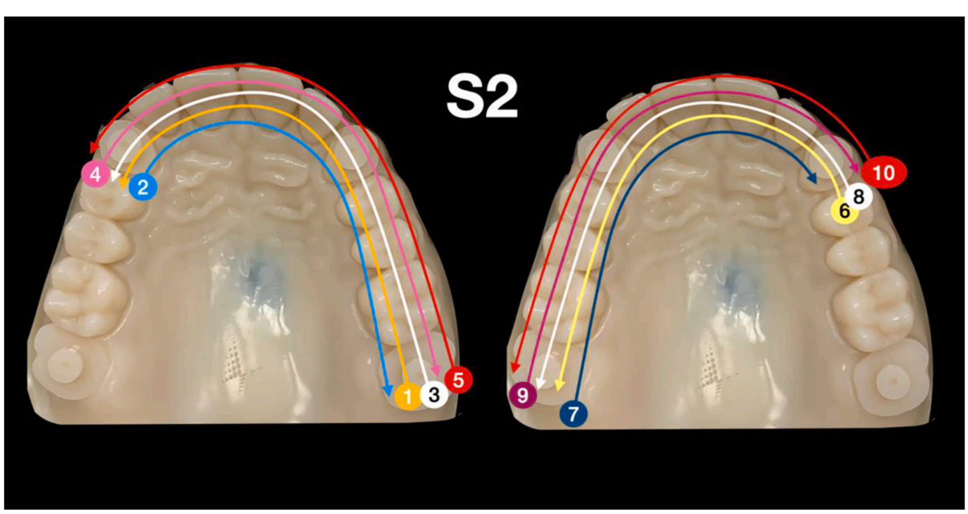

Fig. 2. S2 strategy corresponds to the Latham technique.

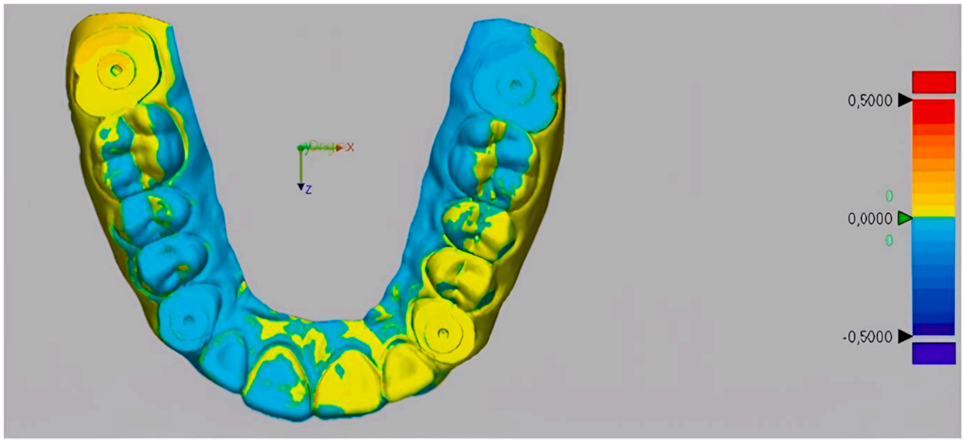

Fig. 4. Color map of treatment scan with respect to control model (The color scale is calibrated at 0.5 mm).

Table 1
Mean (standard deviation) for trueness (μm), precision (μm), and scan duration (min) for each IOS and scan strategy.

Scan strategy	Scanner	N	Trueness		Precision		Scan duration	
			Mean	SD	Mean	SD	Mean	SD
S1	Trios 3	10	9.98^{1}	3.11	25.67^{1,2}	5.78	1.24^{1}	0.09
	MEDIT i700	10	10.44^{1}	3.34	39.52^{2}	13.77	1.53^{2}	0.12
	CS 3600	10	24.78^{2}	7.37	76.53^{3}	23.85	1.67^{2}	0.10
	iTero Element 5D	10	12.24^{1}	5.03	44.45^{1}	11.48	1.27^{1}	0.07
S2	Trios 3	10	11.93^{1}	4.20	22.46^{2}	9.51	1.90^{3}	1.15
	MEDIT i700	10	16.33^{2}	7.62	46.24^{2}	15.07	1.80^{3}	0.19
	CS 3600	10	24.05^{2}	3.16	44.93^{2}	11.65	3.74^{3}	1.33
	iTero Element 5D	10	11.53^{1}	2.29	30.19^{2}	15.27	2.07^{3}	1.17
S3	Trios 3	10	8.84^{1}	2.19	31.69^{1}	12.89	1.32^{1}	0.48
	MEDIT i700	10	7.33^{1}	1.96	29.52^{1}	8.98	1.28^{1}	0.11
	CS 3600	10	16.28^{1}	5.18	61.81^{1}	23.07	2.25^{1}	1.22
	iTero Element 5D	10	10.71^{1}	3.19	42.80^{1}	19.30	1.34^{1}	0.09

Same numbers indicate no significant differences between scan strategies for the same IOS.
IOS, intraoral scanner.

distinct scanning mechanisms; other scanners might yield different results. We also investigated some of the available scanning strategies, and other strategies might produce different outcomes in terms of scan accuracy. Moreover, the scanners used in this study are not the latest models, and newer scanners with improved algorithms might reduce errors related to data stitching.

Another limitation is the potential dimensional instability of the resin model used. PMMA matrix degradation can cause dimensional changes, typically occurring over an extended period and under varying temperatures and stress conditions. To mitigate this, we conducted the study within a one-week timeframe, starting immediately after the model was milled. We also used CMM and EOS scans before starting the experiments to obtain precise digital dimensions of the model. During periods when IOS scans were not performed, we stored the milled model in a controlled environment, isolated from external temperature, light, and humidity. These measures should minimize the impact of any potential dimensional instability of the resin model.

Finally, results can be influenced by the dependence on the operator's experience. Using a single operator for all scanners was intended to minimize operator bias and provide a realistic simulation of clinical practice. However, the results may still be influenced by the operator's skill level, as different operators may produce varying outcomes. This dependency on operator proficiency highlights the potential variability in clinical settings and underscores the importance of operator training and experience in achieving accurate results.

Therefore, the results of this study should be interpreted with caution. Further comprehensive research is necessary to validate these findings. Clinical studies are particularly important to determine the practical implications of our results and to understand how they integrate into a fully digital workflow for complete denture fabrication.

In the field of dentistry's IOSs, this study stands out for its unique contribution, systematically investigating how three different scanning strategies influence the precision, trueness, and scan duration of optical impressions from four leading IOSs. Notably, the inclusion of the experimental 'Grow Up' scan strategy (S3) distinguishes this research, introducing a novel approach that has not been explored in previous literature.

Within the above limitations, taking into account that 10–20 μm difference can be clinically less relevant, we can say that:

MEDIT i700: The S3 scanning strategy enhances both trueness and precision. For clinicians using the MEDIT i700, adopting S3 could provide a good balance of reliability and efficiency in obtaining high-quality scans.

CS 3600: Similar to the MEDIT i700, the CS 3600 showed the highest trueness with the S3 strategy. While S2 resulted more precise among the tested strategies, the overall performance suggests that S3 is a valid option for achieving consistent outcomes.

Trios 3 and iTero Element 5D: The three scanning strategies seem to offer equivalent trueness, with S2 offering higher precision compared to the other strategies. Clinicians may select any strategy based on their workflow and experience, as all options provide satisfactory performance in practice.

5. Conclusions

Within the limitations of this laboratory study due to the study design, experimental model, IOSs employed and operator's experience, scanning strategy significantly influenced the precision, accuracy, and scan duration of optical impressions. In particular, the S2 strategy achieved the best precision with all devices except for MEDIT i700, whereas S3 provided the best trueness with CS 3600 and MEDIT i700. Strategy S2 exhibited the shortest scan duration among the tested devices. Overall, strategy S3 showed the best combination of trueness, precision, and scan duration with MEDIT i700.

CRediT authorship contribution statement

Luca Ortensi: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization. **Giusy Rita Maria La Rosa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Stefania Ciletta:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Francesco Grande:** Formal analysis, Visualization, Writing – review & editing. **Eugenio Pedullà:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization.

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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