Heliyon 10 (2024) e31063

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Evaluation of the accuracy of seven intraoral scanners for the full dentate and partially edentulous complete-arch mandibular casts: An *in vitro* comparison

Xin Wang [1], Fang Zhang [1], Dan Ma, Xiaolan Ye, Xiaojuan Zheng, Ruifang Ren, Nan Ren [**], Shizhu Bai [*]

State Key Laboratory of Oral and Maxillofacial Reconstruction and Regeneration & National Clinical Research Center for Oral Diseases & Shaanxi Key Laboratory of Stomatology, Digital Center, School of Stomatology, The Fourth Military Medical University, Xi'an, Shaanxi, China

ABSTRACT

Statement of problem: Intraoral scanners (IOSs) are widely used in dentistry, providing high accuracy in short-range scanning. Nevertheless, when scanning the full dental arch, it remains a challenge. Furthermore, there is a lack of studies reporting the differences in scan accuracy between dental arches with large-span mucosal areas and fully dentate casts or optimal IOS selection for different dental statuses.

Purpose: This study aimed to evaluate the accuracy and scanning time of different IOSs for full dentate (FD) and partially edentulous (PE) casts with missing teeth in the #34–#44 range and to determine the IOSs with the optimal clinical adaptability and scanning accuracy for different complete-arch casts.

Material and methods: Reference scans of two complete-arch (FD and PE) casts were obtained using a laboratory scanner (Ceramill Map 600). Subsequently, the same casts were scanned ten times each by seven IOSs (3Shape Trios 3, CS3600, Planmeca Emerald, iTero Element 5D, Medit i500, BAMBOO B1, and Shining Aoralscan 3), and the scanning time was recorded. The test data were superimposed on the reference scans for the selected areas, and three-dimensional deviations between the reference and test casts (trueness), and between test casts (precision) were determined using reverse engineering software (Geomagic Wrap). The dataset was analyzed using a two-factor analysis of variance with post-hoc Bonferroni tests.

Results: Two-factor analysis of variance revealed significant differences in accuracy and scanning time for different casts ($P < 0.001$) and IOSs ($P < 0.001$). For the FD cast, the i500 (0.35 ± 0.11 mm trueness) and CS3600 (0.23 ± 0.12 mm precision) performed worse than the remaining scanners. For the PE cast, the BAMBOO B1(0.89 ± 0.58 mm trueness; 0.88 ± 0.48 mm precision) performed worse than the remaining scanners. There were no differences in the accuracy of scanning between the Element 5D and Emerald for both cast types. However, the scanning time differed significantly between the different IOSs ($P < 0.001$). Regardless of the cast type, the fastest and slowest scans were performed by the Trios3 and CS3600 scanners respectively.

Conclusions: The accuracy and scanning time differed between the different IOSs and types of complete-arch casts.

* Corresponding author. State Key Laboratory of Oral and Maxillofacial Reconstruction and Regeneration & National Clinical Research Center for Oral Diseases & Shaanxi Key Laboratory of Stomatology, Digital Center, School of Stomatology, The Fourth Military Medical University, Xi'an, Shaanxi, 710032, China.

** Corresponding author. State Key Laboratory of Oral and Maxillofacial Reconstruction and Regeneration & National Clinical Research Center for Oral Diseases & Shaanxi Key Laboratory of Stomatology, Digital Center, School of Stomatology, The Fourth Military Medical University, Xi'an, Shaanxi, 710032, China.

E-mail addresses: rennan926@hotmail.com (N. Ren), baishizhu@foxmail.com (S. Bai).

[1] Xin Wang and Fang Zhang contributed equally to this work

https://doi.org/10.1016/j.heliyon.2024.e31063
Received 24 July 2023; Received in revised form 11 April 2024; Accepted 9 May 2024
Available online 10 May 2024
2405-8440/

1. Introduction

With continuous advances in digital technology, digital dental impressions have rapidly developed [1]. Compared with traditional impression techniques that produces physical casts or impressions, digital impression techniques can improve patient comfort and satisfaction, visualize the three-dimensional (3D) morphology inside a patient's mouth, improve the efficiency of doctor–patient communication, and reduce chairside operation time. Computer-aided design and fabrication of restorations based on digital casts can avoid the accumulation of errors caused by complex traditional impression procedures and can also improve accuracy and productivity [2–5]. Intraoral scanners (IOSs), which are critical devices for digital intraoral impressions, were initially used for single-tooth restorations; however, they can now be applied to multi-unit fixed prostheses, removable partial prostheses, and, most recently, full-arch rehabilitations [6].

The accuracy of an IOS directly affects the accuracy of the fabricated restorations. Currently, IOSs can provide adequate scanning accuracy for single-crown, short-span tooth-, and implant-supported fixed dental prostheses [7–9]. However, studies have indicated that an increase in span length results in reduced scan accuracy, particularly for full arches [10]. Furthermore, the more extensive the tooth loss, the higher the cumulative error caused by the stitching process and the lower the scanning accuracy. Therefore, currently, obtaining full-arch scans remains challenging, potentially resulting in ill-fitting restorations or restorations that are difficult to seat in clinical settings [9,11]. Full-arch scans are also used for extensive dentition defects; however, the accuracy of such scans tends to be lower than that achieved with full dentition. This is due to the lack of features used for accurate alignment and stitching, mucosal changes during mandibular movements [12], and similarity of the morphology of the scan bodies for implant-supported restorations when forming the 3D image comprising the mucosal scans of edentulous areas [13]. The inability of IOSs to align and stitch images accurately, and the accumulation of stitching errors due to the wide range of scans, leads to a further decrease in accuracy [14–18].

The post-processing principle used by the scanner on the scanned feature images, as well as the alignment and stitching algorithm of the scan track, are critical factors that affect the accuracy of IOSs. Whether IOSs can accurately obtain data from patient with partial edentulism for the development of prosthetics has become a crucial area of research for clinical applications. Few reports have investigated the accuracy of IOSs for scanning dental arches within a short span of mucosal areas [7,19–21]; however, to date, no study has reported the differences in scan accuracy between dental arches with large-span mucosal areas and full dentate (FD) casts, differences in scanning time, or optimal IOS selection. Moreover, previous studies have reported different casts for different dental statuses, undoubtedly introducing additional errors in comparison process.

In this study, the aim was to evaluate the accuracy and scanning time of different IOSs for FD and partially edentulous (PE) casts and to determine the IOSs with the optimal clinical adaptability and scanning accuracy for different complete-arch casts. The null hypothesis was that there would be no significant differences in the scanning accuracy (trueness and precision) and scanning time between different IOSs and different casts.

2. Material and methods

2.1. Design and processing of the casts

To obtain the reference cast data, a mandibular typodont (Nissin, Tokyo, Japan) was scanned using a high-accuracy laboratory scanner (Ceramill Map 600; Amann Girrbach AG, Koblach, Austria), and the data were saved in the standard tessellation language (STL) format. Data from the mandibular standard cast were imported into a reverse engineering software (Geomagic Wrap 2021; 3D Systems, USA) to create a removable module containing teeth #34–#44. This module was subsequently duplicated, and teeth #34–#44 were removed, retaining the right and left lateral second premolars, first molar, and second molar to simulate the alveolar ridge in the edentulous area of the mandibular anterior teeth. A mandibular cast was made with the corresponding groove size according to the inlay surface size of the aforementioned modules (Fig. 1. A). The completed cast and removable modules were printed using a 3D printer (Pro95; SprintRay, Hangzhou, China) with the resin model material (SP-RM0409, SprintRay, Hangzhou, China), and the two modules were inserted into the cast to create an FD cast (Fig. 1. B) and a PE cast respectively (Fig. 1. C).

2.2. Scanning process and digital data acquisition

The following seven IOSs, with the indicated software versions, were used to scan the two casts: Trios 3 v. 20.1.3 (3Shape A/S,

Fig. 1. Mandibular cast. A. Detachable modules. B. Full dentate cast. C. Partially edentulous cast.

Copenhagen, Denmark), CS3600 v. 7.0.23.0 (Carestream, Rochester, NY, USA), Emerald v.6.0.1.812 (Planmeca, Helsinki, Finland), iTero Element 5D v. 2.7.9.885 (Align Technology Inc, Carlsbad, CA, USA), Aoralscan 3 v.1.0.0.3123 (Shining 3D, Hangzhou, China), BAMBOO B1 v.1.14.0.3665 (Freqty, Ningbo, China), and Medit i500 v. 1.2.1 (Medit, Seoul, South Korea).

The required sample size was calculated using G*Power v.3.1.9.7 (Heinrich-Heine-Universität Düsseldorf). The following input parameters were used: effect size, f = 0.4; error, $\alpha = 0.05$; and power, 0.95. A total sample size of 137 casts for the 14 scan groups (seven IOSs scanning both FD and PE casts) produced a calculated power of 0.9503. Considering the sample sizes of previous similar studies [7,22], it was finally determined that each scanner should perform ten scans of both the FD and PE casts.

All scanning procedures were performed by one surgeon with more than 3 years of experience in scanning. The FD module was affixed to the dental arch cast using temporary adhesive material. The cast to be scanned was fixed by a magnet to a phantom head with artificial skin, which was adjusted to a suitable position to ensure that the mandibular cast remained stationary under suitable external force. The occlusal surface was parallel to the ground. The scanner head was kept parallel to the occlusal surface, and the buccolingual surface was scanned at an angle of 45°–90°to the long axis of the teeth. The scanning strategy for both the FD and PE casts was as follows: the scanner head was placed on the occlusal surface of the molars—initially on the right side (#47)—and subsequently moved toward the anterior region with an "S" motion, followed by scanning parallel to the occlusal surface when it reached the left side, as far as #37; thereafter, starting from tooth #37, the head scanned lingually to #47, moving from #47 distally to the buccal side and finally ending at the distal side of #37. Post-scan inspections included verifying the completeness of teeth with clear visualization of the incisal edges and cusps, ensuring that the scanning range on the buccolingual side extended 2–3 mm below the free gingiva margin, checking for any excess meshes along the edges, and confirming that the overall scan data were complete and unstratified.

The FD casts were scanned by the Ceramill Map 600, and the data obtained were exported in the STL format to obtain the digital reference cast. To scan the PE cast, the temporary adhesive material was thoroughly cleaned after the removal of the FD anterior tooth area accessories, and the edentulous module was installed and subsequently checked to ensure accuracy of placement and that it remained stationary under external force. Following the same procedure as mentioned above, PE casts were scanned using an intraoral scanner and Ceramill Map 600. Each IOS (n = 7) scanned each cast (n = 2) 10 times for a total of 140 scans, and data were exported in the STL format as test casts.

The scanning time was recorded for each scan of the complete arch, beginning with the click that activated the scanning mode of the IOS and ending when all data of the complete arch scan were obtained. Further processing of the scanned data was then initiated. The scan was reperformed and retimed in cases of missing data, including cases in which the scan was incomplete.

2.3. Data processing and 3D comparison

Accuracy is the most important metric for evaluating the quality of digital impressions acquired using IOSs. According to the International Organization for Standardization [23], accuracy is represented by trueness, defined as the estimation of how close the measured value is to the real value, and precision, defined as the deviation between repeated measurements performed on the same object (i.e., repeatability).

2.4. Evaluation of trueness

Using Geomagic Wrap software, each dataset from all test cast scans (n = 10) within each group (n = 14) was individually superimposed on the corresponding reference cast using a three-point alignment. Thereafter, the test data were aligned to reference

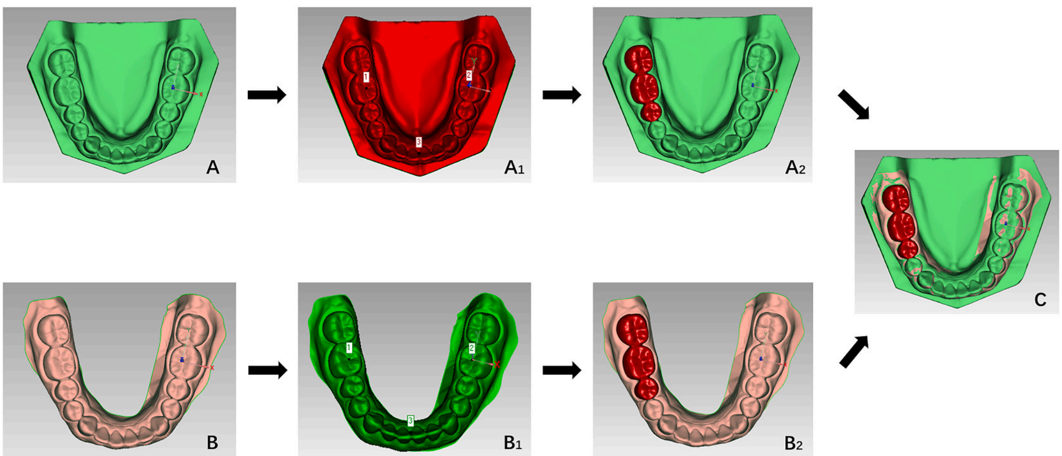

Fig. 2. Alignment process. A. Full dentate reference cast. B. Full dentate test cast. A_1, B_1. Three points are identified for initial alignment. A_2, B_2. Teeth #45, #46, and #47 of the reference and test casts are selected for regional alignment. C. Positional relationship between reference and test cast after regional alignment.

data by the common area (#45, #46, and #47) using the best-fit algorithm (Fig. 2).

The common area (#35, #36, and #37) of the reference and test casts were selected and trimmed (Fig. 3). The root mean square (RMS) value (mm) of deviation in the selected area from the reference data was calculated using a 3D comparison command in the software to obtain the value of trueness. A higher RMS value indicates inferior trueness.

2.5. Evaluation of precision

Precision was calculated as the RMS value after the scanned cast images within a group were aligned with each other, regardless of the reference cast. To determine the RMS, the scanned 3D casts in each group (n = 10) were paired to form 45 combinations, and each pair was aligned (as described above) on one side. The 3D deviation of the other side was calculated to obtain the precision value. A higher RMS value indicates inferior precision.

2.6. Statistical analysis

SPSS 25 (IBM Corp, Armonk, NY, USA) was used to analyze accuracy and scanning time. The normality of datasets was tested using the Kolmogorov–Smirnov test; homogeneity of variance was tested using Levene's test; and descriptive analyses were performed on the datasets of each group. A two-factor analysis of variance (ANOVA) was applied to determine the effects of the two factors (different casts and different IOSs) on trueness, precision, and scanning time. One-way ANOVA was applied to further determine the effects of each factor on trueness, precision, and scanning time in the same block group. Bonferroni correction was performed for post-hoc multiple pairwise comparisons.

3. Results

The two-factor ANOVA showed a significant interaction effect of different IOSs with different scanning casts on the accuracy and scanning time ($P < 0.001$). The two cast types ($P < 0.001$) and seven scanners ($P < 0.001$) differed significantly in terms of accuracy and scanning time. To further determine the effect of each factor on the three evaluation indices (trueness, precision, and scan time), a one-way ANOVA was performed separately for each factor in each block group. Descriptive analyses of the datasets for each group are shown in Table 1, and a representative color map of trueness discrepancies measured among each group test is shown in Fig. 4.

3.1. Comparison of trueness

Fig. 5 shows a comparison of trueness of the FD and PE cast scans from the seven different scanners. For the FD cast, there was a significant difference ($P < 0.001$) in the trueness of the seven IOSs. The scanning system i500 (0.35 ± 0.11 mm) (mean ± standard) and CS3600 (0.29 ± 0.08 mm) were within the same value range ($P > 0.05$) and presented a significant lower trueness than the BAMBOO B1 (0.19 ± 0.08 mm) (i500: $P < 0.001$; CS3600: $P < 0.05$), the Emerald (0.16 ± 0.02 mm) (i500: $P < 0.001$; CS3600: $P < 0.01$), the Trios 3 (0.12 ± 0.07 mm) (i500: $P < 0.001$; CS3600: $P < 0.001$), the Aoralscan 3 (0.12 ± 0.03 mm) (i500: $P < 0.001$; CS3600: $P < 0.001$) and the Element 5D (0.11 ± 0.04 mm).(i500: $P < 0.001$; CS3600: $P < 0.001$), There was also a significant

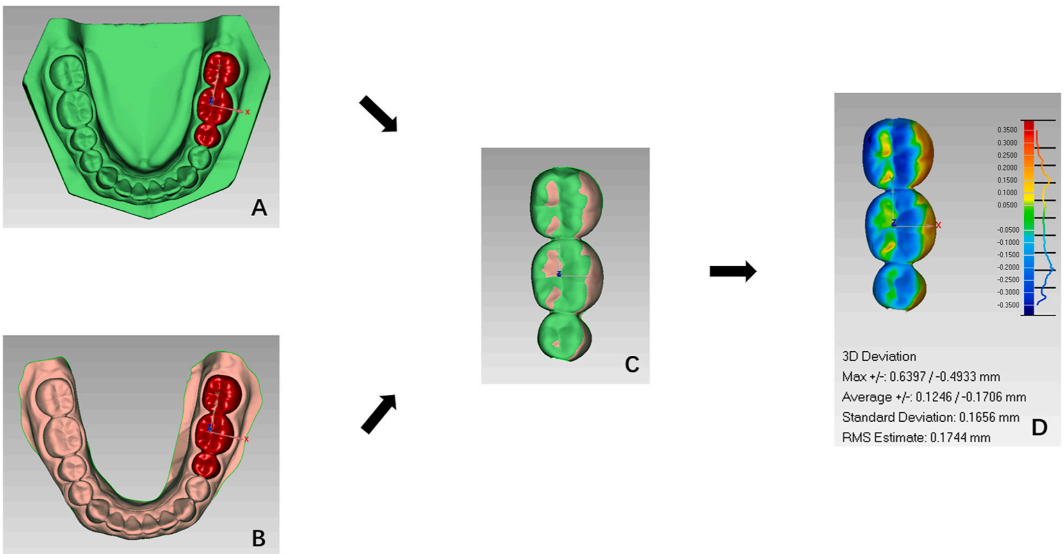

Fig. 3. Determining the RMS value of the selection area. Teeth #35, #36, and #37 of the reference (A) and test casts (B) are aligned (C). The 3D deviation of the test cast from the reference cast is measured (D). RMS, root mean square.

Table 1
Mean deviation (±SD) of trueness, precision, and scanning time for seven IOSs (mm).

IOS	Arch	trueness (mm)		precision (mm)		time(s)	
		Mean ± SD	95%CI	Mean ± SD	95%CI	Mean ± SD	95%CI
Trios 3	FD	0.12 ± 0.07[b]	(0.07–0.16)	0.12 ± 0.05[cd]	(0.10–0.13)	34.60 ± 1.65[d]	(33.42–35.78)
	PE	0.22 ± 0.06[c]	(0.17–0.26)	0.20 ± 0.08[b]	(0.17–0.22)	29.70 ± 1.83[f]	(28.39–31.01)
CS3600	FD	0.29 ± 0.08[a]	(0.23–0.34)	0.23 ± 0.12[a]	(0.20–0.27)	84.60 ± 4.52[a]	(81.36–87.84)
	PE	0.58 ± 0.08[b]	(0.52–0.64)	0.16 ± 0.06[bc]	(0.14–0.18)	82.10 ± 4.15[a]	(79.13–85.07)
Element 5D	FD	0.11 ± 0.04[b]	(0.09–0.14)	0.14 ± 0.06[bc]	(0.12–0.15)	58.30 ± 6.34[c]	(53.76–62.84)
	PE	0.15 ± 0.05[c]	(0.11–0.19)	0.13 ± 0.05[bc]	(0.12–0.15)	62.60 ± 3.53[c]	(60.07–65.13)
Emerald	FD	0.16 ± 0.02[b]	(0.14–0.17)	0.09 ± 0.04[d]	(0.08–0.11)	69.50 ± 5.40[b]	(65.64–73.36)
	PE	0.13 ± 0.06[c]	(0.09–0.18)	0.11 ± 0.04[bc]	(0.09–0.12)	68.50 ± 4.77[b]	(65.09–71.91)
i500	FD	0.35 ± 0.11[a]	(0.27–0.43)	0.12 ± 0.05[cd]	(0.10–0.13)	70.00 ± 1.83[b]	(68.69–71.31)
	PE	0.28 ± 0.03[bc]	(0.26–0.30)	0.08 ± 0.03[c]	(0.07–0.09)	55.10 ± 3.18[d]	(52.83–57.37)
BAMBOO B1	FD	0.19 ± 0.08[b]	(0.13–0.24)	0.16 ± 0.08[b]	(0.14–0.19)	63.00 ± 6.13[c]	(58.62–67.38)
	PE	0.89 ± 0.58[a]	(0.28–1.30)	0.88 ± 0.48[a]	(0.74–1.02)	70.70 ± 3.68[b]	(68.07–73.33)
Aoralscan 3	FD	0.12 ± 0.03[b]	(0.10–0.15)	0.08 ± 0.04[d]	(0.07–0.09)	58.20 ± 3.12[c]	(55.97–60.43)
	PE	0.17 ± 0.03[c]	(0.16–0.19)	0.07 ± 0.03[c]	(0.06–0.08)	48.40 ± 2.46[e]	(46.64–50.16)

IOS, intraoral scanner; FD, full dentition; PE, partial edentulism; SD, standard deviation; CI, confidence interval. Groups with different letters indicate significant differences in IOSs in the same cast group by post-hoc Bonferroni tests ($p < 0.05$).

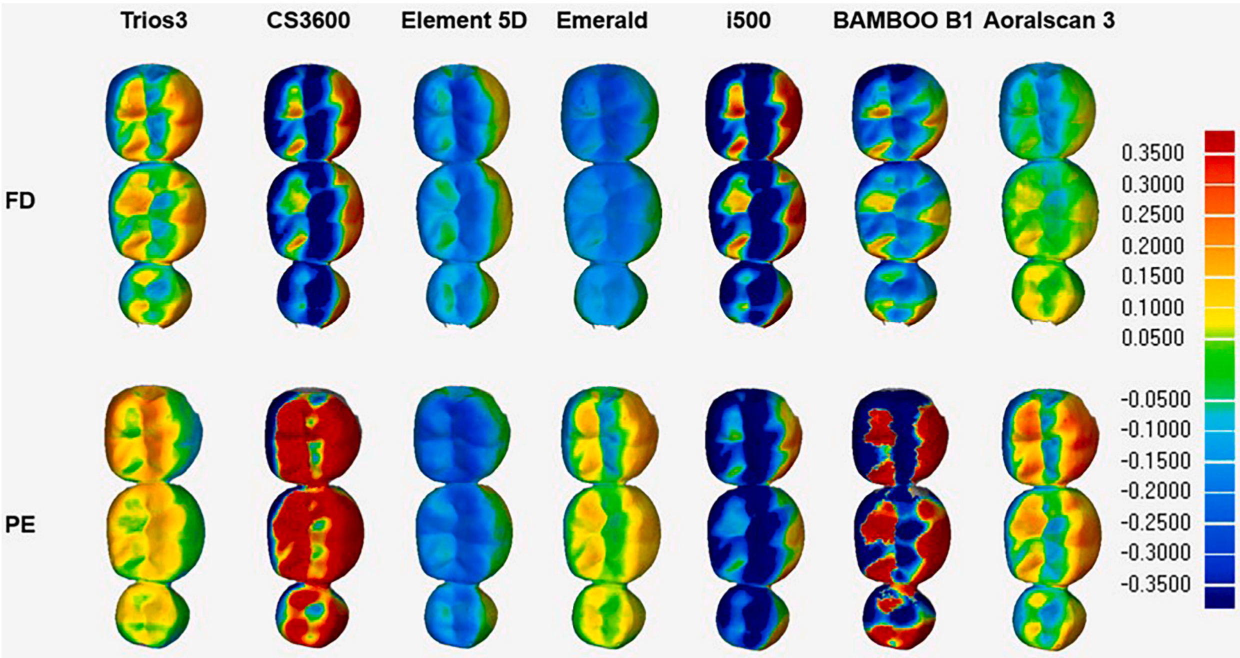

Fig. 4. Representative color map of trueness discrepancy measured among each group. Data provided in millimeters (mm). Max/min nominal 0.05 mm (green). Max/min critical 0.35 mm (dark red and dark blue). RMS, root mean square. FD, full dentition; PE partial edentulism. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

difference between IOSs for PE casts ($P < 0.001$). The scanning system BAMBOO B1 (0.89 ± 0.58 mm) presented a significant lower trueness than the CS3600 (0.58 ± 0.08 mm) ($P < 0.05$), the i500 (0.28 ± 0.03 mm) ($P < 0.001$), the Trios 3 (0.22 ± 0.06 mm) ($P < 0.001$), the Aoralscan 3 (0.17 ± 0.03 mm) ($P < 0.001$), the Element 5D (0.15 ± 0.05 mm) ($P < 0.001$) and Emerald (0.13 ± 0.06 mm) ($P < 0.001$).Among the seven scanners, Trios 3 ($P < 0.01$), CS3600 ($P < 0.001$), Aoralscan 3 ($P < 0.01$), and BAMBOO B1 ($P < 0.01$) scanned the PE cast with significantly higher RMS values than the FD cast.

3.2. Comparison of precision

The precision deviations of the seven IOSs for the FD and PE casts are shown in Fig. 6. For the FD cast, the precision of the seven scanners differed significantly ($P < 0.001$), with the precision of the CS3600 (0.23 ± 0.12 mm) being the lowest and that of the Aoralscan 3 (0.08 ± 0.04 mm) being the highest. The precision of the seven scanners when scanning the PE cast also differed

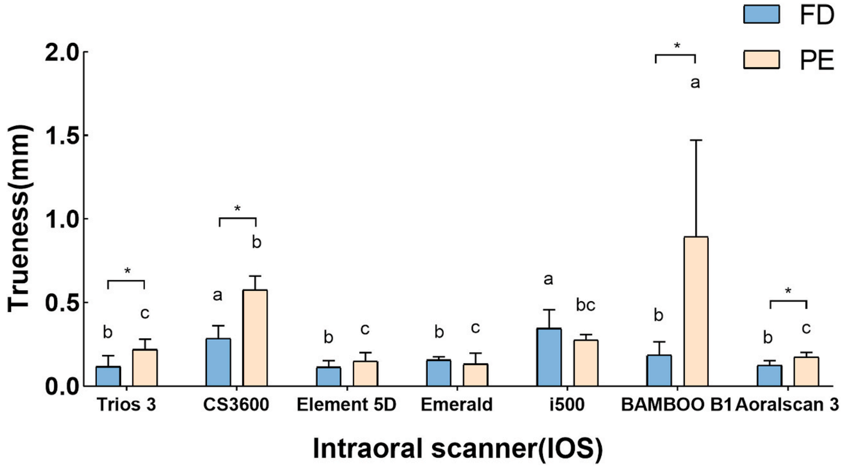

Fig. 5. Trueness analysis: 3D deviations (in mm) for the FD and PE casts by seven types of IOSs. *: P < 0.05, comparing trueness of the FD and PE casts for one scanner type. IOSs with different lower-case letters for the same cast type produced significantly different trueness (P < 0.05). FD, full dentition; PE, partial edentulism; IOS, intraoral scanner.

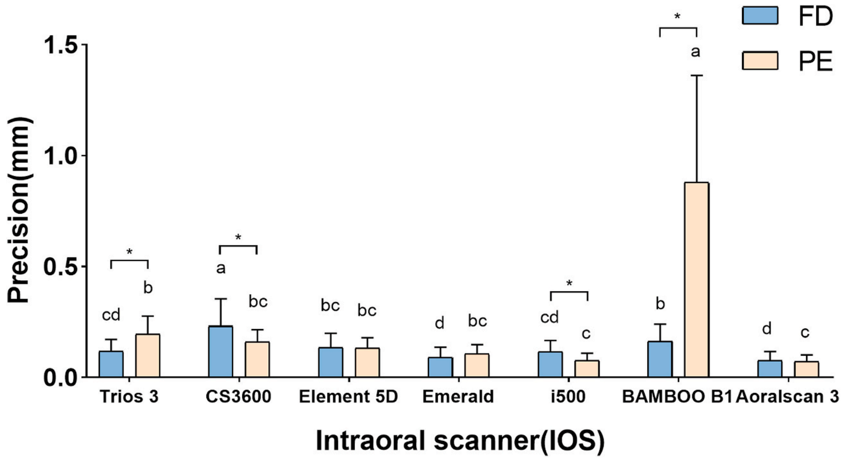

Fig. 6. Precision analysis: 3D deviations (in mm) for the FD and PE casts by seven types of IOSs. *: P < 0.05 comparing the precision of FD and PE casts for one scanner type. IOSs with different lower-case letters for the same cast type produced significantly different precision (P < 0.05). FD, full dentition; PE, partial edentulism; IOS, intraoral scanner.

significantly (P < 0.001), with the BAMBOO B1 (0.88 ± 0.48 mm) having the lowest precision and Aoralscan 3 (0.07 ± 0.03 mm) having the highest precision. The precision of the Trios 3 (P < 0.001) and BAMBOO B1 (P < 0.001) were significantly lower for the PE cast than for the FD cast, while the precision of the CS3600 (P < 0.01) and the i500 (P < 0.001) were significantly higher for the PE cast than for the FD cast.

3.3. Comparison of scanning time

The scanning time of the seven scanners for the FD and PE casts is shown in Fig. 7. The scanning time was significantly different across instruments, irrespective of cast types (P < 0.001). Trios 3 had the shortest scanning time, whereas the CS3600 had the longest. The i500 (P < 0.001), BAMBOO B1 (P < 0.01), and Aoralscan 3 (P < 0.001) had significantly different scanning time between casts.

4. Discussion

According to the results obtained in this experiment, the null hypothesis that there are no significant differences in the accuracy and scanning time between IOSs when scanning the same type of cast was rejected, whereas that regarding differences between casts for the same IOS was partially rejected.

Although the experimental design, cast selection, operator experience, brand and version of the scanner, and software and methods

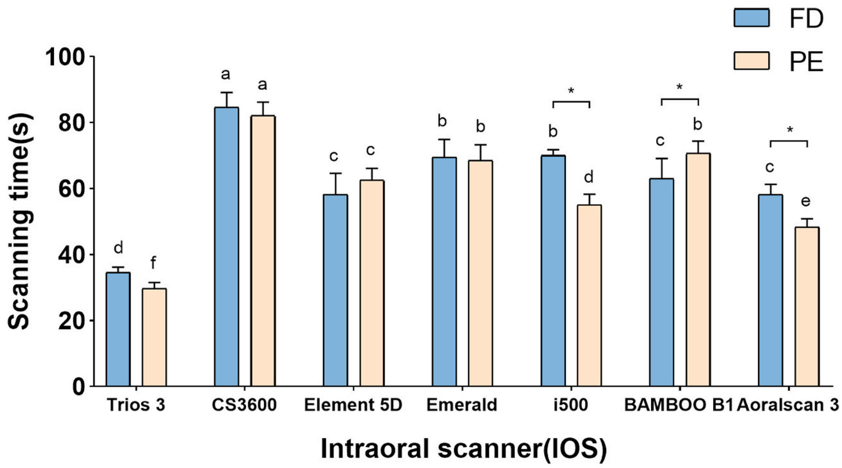

Fig. 7. Time analysis: Scanning time (in second) for the FD and PE casts by different IOSs. *: $P < 0.05$, comparing the scanning time of FD and PE casts for one scanner type. IOSs with different lower-case letters for the same cast type produced significantly different scanning time ($P < 0.05$). FD, full dentition; PE, partial edentulism; IOS, intraoral scanner.

used for analysis differed from other published articles, this experiment clearly shows that there are some challenges pertaining to trueness and precision when using an IOS for scanning the full arch. The mean trueness RMS values of all seven tested IOSs for both the FD and PE casts were less than 0.3 mm, excluding the i500 for FD casts and BAMBOO B1 and CS3600 for PE casts. The average precision RMS value of all IOSs for the FD and PE casts was less than 0.25 mm, except for BAMBOO B1 for PE casts. The values obtained in the present study were higher than those obtained previously because the best-fit alignment of the full arch, as used in other studies, was not implemented here as it induces the uniform distribution of deviation across the arch, and several authors have argued that RMS values obtained in this manner are lower than their true values [24–26]. A difference in the scanning error between the start and end of the scan, with the accuracy decreasing further from the start of the scan, has also been reported [23]. The wider the scanning area, the more stitching errors and the lower the accuracy of the scan [4]. Therefore, this experiment evaluated accuracy by choosing only three teeth on the right side for the best-fit alignment (i.e., the area with a relatively small deviation from the scan start) and measuring the RMS value for three teeth on the left side (i.e., the area farthest from the scan start). This approach was performed for the reference best-fit alignment by selecting the start of the scan, which was least likely to have undergone a change. This minimized scanning errors for the area of interest and evaluated deviation not only according to the 3D deviation away from the scan start area but also according to the stitching errors that accumulated during the scanning process.

The inlay detachable assembly designed in this experiment made the FD and PE casts consistent, except for in the anterior tooth area, which had the advantage of greatly reducing printing errors and material problems that may result in deviations in areas where the casts should be identical. After scanning the FD cast using the laboratory scanner and the IOSs, the detachable module was replaced, and the PE cast was scanned, which ensured cast consistency throughout the scans for each model.

For scanning the FD cast, the Element 5D had the highest trueness, and the CS3600 had the lowest precision; for the PE cast, the Emerald had the highest trueness, and the BAMBOO B1 had the lowest precision. There were no significant differences in accuracy between the scans of the FD and PE casts with the Element 5D, Emerald, and i500 IOSs, although there were differences between the remaining four scanners, which could be mainly attributed to two reasons. First, tracking errors are caused by scanning mucosa or gingiva that lack surface markings (e.g., edentulous jaws), where the image data acquired by the IOS cannot be aligned with the acquired images, causing the system to lose track of the location of the scan and possibly yielding a lower accuracy of PE scans compared with that of FD scans [14,16,17]. Second, offset error can also be caused by measurement error. All sensors of a scanner produce measurement errors, especially with long-range scanning, such as in full-arch scanning, when sensor stitching errors accumulate during the scanning process and eventually lead to an offset error in the accuracy of the scan trajectory, affecting the quality of the scan results. The deviation was relatively large for the cross-arch scans [22,27]. Both these error types would have resulted in lower trueness when scanning the PE cast.

In consideration of the reasons presented above, for patients with partial edentulism in clinical practice, the data obtained by IOSs may be greatly biased, suggesting that removable partial dentures, made according to digital impressions cannot be successfully positioned or may not fit the remaining teeth. All tested scanners met the standard for clinical denture suitability—a trueness deviation of less than 0.311 mm [28], except for the i500, CS3600, and BAMBOO B1 scanners. Therefore, this study provided a reference for the selection of scanners for patients with dental defects.

The Aoralscan 3 exhibited the best precision for both the FD and PE casts. The least stable precision was shown by the CS3600 for the FD cast and by the BAMBOO B1 for the PE cast. Precision represents the repeatability and reproducibility of a scanner [29]. For scanners with unstable precision, better performance can be achieved by temporarily attaching small objects with pronounced feature marks to the edentulous area during the scanning process [4].

The precision of PE scans conducted using the Trios 3 and BAMBOO B1 devices was significantly higher than that of FD scans, whereas the precision of PE scans using the CS3600 ($P < 0.01$) and i500 ($P < 0.001$) devices was significantly lower than that of FD scans. This finding contradicts our initial expectation, which posited that an expansion in the edentulous space would lead to an increased scanning distance of the mucosa increases, consequently resulting in a reduction in precision for IOSs [30]. Currently, scanner manufacturers provide limited information on data post-processing principles, making it difficult to obtain a deeper understanding regarding this aspect. However, it is worth mentioning that the scanning principles of the CS3600 and i500 IOSs are based on a dual-camera optical triangulation technique. However, it remains unclear whether this scanning approach contributes to enhanced scanning accuracy within a specific range or length of the edentulous region. Interestingly, Braian et al. [29] evaluated the scanning accuracy of FD and edentulous dental arches using different scanners and observed similar outcomes. The precision of the CS3600 scanner when scanning edentulous casts in the short range was larger than that for FD casts.

Our study presents a different perspective compared to the findings reported by Lee et al. [31], who investigated the influence and accuracy of scanners and concluded that the brand of IOS did not significantly impact scanning accuracy. However, it is noteworthy that the scope of our investigation involved the assessment of seven different IOS brands, including the CS3600 and i500 examined by Lee et al. While our results suggest a potential association between scanning accuracy and IOS brand, it is crucial to recognize the variations in experimental designs and scanner types, which may contribute to divergent conclusions.

The digital impressions acquired by IOSs are formed by the progressive stitching of the acquired images, and the scanner must repeatedly identify the acquired images to reposition them because the tracking position is lost. Another important consideration is that as the scan time increases, scan trueness decreases [32]. Our observations align with this trend: the Trios 3, with the shortest scan time, exhibited relatively high trueness, while the CS3600, requiring the longest scan time, demonstrated relatively lower trueness. It is important to note that while these observations align with previous findings, establishing a direct causal link between scan time and trueness requires further investigation. In summary, users can draw conclusions based on the findings of this study and select the most suitable scanner for different casts and performance requirements.

This study has few limitations. Because our study was conducted *in vitro*, clinical conditions, under which saliva, temperature, humidity, and soft tissues in the oral cavity can affect the accuracy of the scanning data, could not be simulated. Additionally, the ability of different IOSs to acquire images *in vitro* and intraorally may not be similar; therefore, this experiment may only serve as a general guide. We only used an FD cast and a full arch cast with anterior tooth loss, and the effect of the length and distribution of the edentulous area could not be studied. Future studies should examine whether the location and extent of missing teeth affects scanning accuracy. Of note, it was found that, in the process of comparing the 3D deviation after selecting the area and aligning it, if the two casts were far apart, the software algorithm automatically found the closest point in the test scan to the reference scan instead of the corresponding point, which was farther away; thus, the data values obtained invariably reduced the amount of 3D deviation, affecting the accuracy of the final restoration. A novel evaluation approach to fix data distortion is warranted.

5. Conclusions

Based on the results of this *in vitro* study, the following conclusions can be drawn:

1) Trueness, precision, and scanning time were influenced by the IOS and type of cast being scanned.
2) The i500 and CS3600 were not suitable for PE casts with high trueness requirements. The CS3600 showed the lowest repeatability when scanning PE casts, while the Aoralscan demonstrated the highest repeatability. Regarding the scanning of PE casts, all scanners, except for the i500, CS3600, and BAMBOO B1, exhibited clinically acceptable trueness (deviation: <0.311 mm).The BAMBOO B1 had the lowest repeatability, while the Aoralscan and i500 displayed the highest repeatability.
3) The Element 5D and Emerald scanned FD and PE casts with no significant difference in accuracy.
4) Regardless of the type of cast scanned, the scanning time of the Trios 3 was the shortest, whereas that of the CS3600 was the longest.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

CRediT authorship contribution statement

Xin Wang: Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fang Zhang:** Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dan Ma:** Software, Methodology, Formal analysis, Data curation. **Xiaolan Ye:** Software, Methodology. **Xiaojuan Zheng:** Software, Methodology. **Ruifang Ren:** Supervision, Methodology. **Nan Ren:** Writing – review & editing, Visualization, Validation, Methodology, Funding acquisition, Formal analysis, Data curation. **Shizhu Bai:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

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.

References

[1] R. Richert, A. Goujat, L. Venet, G. Viguie, S. Viennot, P. Robinson, J.-C. Farges, M. Fages, M. Ducret, Intraoral scanner technologies: a review to make a successful impression, J Healthc Eng 2017 (2017) 8427595.
[2] A. Ender, A. Mehl, Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision, J. Prosthet. Dent 109 (2013) 121–128.
[3] Y.R. Gallardo, L. Bohner, P. Tortamano, M.N. Pigozzo, D.C. Laganá, N. Sesma, Patient outcomes and procedure working time for digital versus conventional impressions: a systematic review, J. Prosthet. Dent 119 (2018) 214–219.
[4] T. Shimizu, A. Tasaka, J. Wadachi, S. Yamashita, A new proposal for improving the accuracy of intraoral scanning for partially edentulous residual ridge, J Prosthodont Res 67 (2) (2023) 246–254.
[5] F. Mangano, A. Gandolfi, G. Luongo, S. Logozzo, Intraoral scanners in dentistry: a review of the current literature, BMC Oral Health 17 (2017) 149.
[6] M.L.C. Aragón, L.F. Pontes, L.M. Bichara, C. Flores-Mir, D. Normando, Validity and reliability of intraoral scanners compared to conventional gypsum models measurements: a systematic review, Eur. J. Orthod. 38 (2016) 429–434.
[7] G. Ochoa-López, R. Cascos, J.L. Antonaya-Martín, M. Revilla-León, M. Gómez-Polo, Influence of ambient light conditions on the accuracy and scanning time of seven intraoral scanners in complete-arch implant scans, J. Dent. 121 (2022) 104138.
[8] M. Zimmermann, A. Ender, A. Mehl, Local accuracy of actual intraoral scanning systems for single-tooth preparations in vitro, J. Am. Dent. Assoc. 151 (2020) 127–135.
[9] K. Son, M.-U. Jin, K.-B. Lee, Feasibility of using an intraoral scanner for a complete-arch digital scan, part 2: a comparison of scan strategies, J. Prosthet. Dent S0022–3913 (21) (2021) 285–287.
[10] C. Wulfman, A. Naveau, C. Rignon-Bret, Digital scanning for complete-arch implant-supported restorations: a systematic review, J. Prosthet. Dent 124 (2020) 161–167.
[11] A. L, A. M, J. D, S. T, R. V, Error propagation from intraoral scanning to additive manufacturing of complete-arch dentate models: an in vitro study, J. Dent. 121 (2022).
[12] P. Ribeiro, M. Herrero-Climent, C. Díaz-Castro, J.V. Ríos-Santos, R. Padrós, J.G. Mur, C. Falcão, Accuracy of implant casts generated with conventional and digital impressions-an in vitro study, Int. J. Environ. Res. Publ. Health 15 (2018) 1599.
[13] S. Vandeweghe, V. Vervack, M. Dierens, H. De Bruyn, Accuracy of digital impressions of multiple dental implants: an in vitro study, Clin. Oral Implants Res. 28 (2017) 648–653.
[14] S.B.M. Patzelt, S. Vonau, S. Stampf, W. Att, Assessing the feasibility and accuracy of digitizing edentulous jaws, J. Am. Dent. Assoc. 144 (2013) 914–920, https://doi.org/10.14219/jada.archive.2013.0209.
[15] T. Su, J. Sun, Comparison of repeatability between intraoral digital scanner and extraoral digital scanner: an in-vitro study, J Prosthodont Res 59 (2015) 236–242.
[16] H. Hayama, K. Fueki, J. Wadachi, N. Wakabayashi, Trueness and precision of digital impressions obtained using an intraoral scanner with different head size in the partially edentulous mandible, J Prosthodont Res 62 (2018) 347–352.
[17] A. Tasaka, Y. Uekubo, T. Mitsui, T. Kasahara, T. Takanashi, S. Homma, S. Matsunaga, S. Abe, M. Yoshinari, Y. Yajima, K. Sakurai, S. Yamashita, Applying intraoral scanner to residual ridge in edentulous regions: in vitro evaluation of inter-operator validity to confirm trueness, BMC Oral Health 19 (2019) 264.
[18] S. Ren, D. Morton, W.-S. Lin, Accuracy of virtual interocclusal records for partially edentulous patients, J. Prosthet. Dent 123 (2020) 860–865.
[19] W. Renne, M. Ludlow, J. Fryml, Z. Schurch, A. Mennito, R. Kessler, A. Lauer, Evaluation of the accuracy of 7 digital scanners: an in vitro analysis based on 3-dimensional comparisons, J. Prosthet. Dent 118 (2017) 36–42.
[20] F.G. Mangano, O. Admakin, M. Bonacina, H. Lerner, V. Rutkunas, C. Mangano, Trueness of 12 intraoral scanners in the full-arch implant impression: a comparative in vitro study, BMC Oral Health 20 (2020) 263.
[21] C. Bilmenoglu, A. Cilingir, O. Geckili, H. Bilhan, T. Bilgin, In vitro comparison of trueness of 10 intraoral scanners for implant-supported complete-arch fixed dental prostheses, J. Prosthet. Dent 124 (2020) 755–760.
[22] Y. Chen, Z. Zhai, S. Watanabe, T. Nakano, S. Ishigaki, Understanding the effect of scan spans on the accuracy of intraoral and desktop scanners, J. Dent. 124 (2022) 104220.
[23] International organization for standardization, Geneva, Switzerland, ISO 5725-1: 1994, https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/01/18/11833.html, 2018. (Accessed 13 December 2022).
[24] J. Vág, Z. Nagy, B. Simon, Á. Mikolicz, E. Kövér, A. Mennito, Z. Evans, W. Renne, A novel method for complex three-dimensional evaluation of intraoral scanner accuracy, Int. J. Comput. Dent. 22 (2019) 239–249.
[25] J.-F. Güth, D. Edelhoff, J. Schweiger, C. Keul, A new method for the evaluation of the accuracy of full-arch digital impressions in vitro, Clin. Oral Invest. 20 (2016) 1487–1494.
[26] S. O'Toole, C. Osnes, D. Bartlett, A. Keeling, Investigation into the accuracy and measurement methods of sequential 3D dental scan alignment, Dent. Mater. 35 (2019) 495–500.
[27] K. Aswani, S. Wankhade, A. Khalikar, S. Deogade, Accuracy of an intraoral digital impression: a review, J. Indian Prosthodont. Soc. 20 (2020) 27–37.
[28] P. Soltanzadeh, M.S. Suprono, M.T. Kattadiyil, C. Goodacre, W. Gregorius, An in vitro investigation of accuracy and fit of conventional and CAD/CAM removable partial denture frameworks, J. Prosthodont. 28 (2019) 547–555.
[29] M. Braian, A. Wennerberg, Trueness and precision of 5 intraoral scanners for scanning edentulous and dentate complete-arch mandibular casts: a comparative in vitro study, J. Prosthet. Dent 122 (2019) 129–136.e2.
[30] M. Waldecker, W. Bömicke, R. Behnisch, P. Rammelsberg, S. Rues, In-vitro accuracy of complete arch scans of the fully dentate and the partially edentulous maxilla, J Prosthodont Res 66 (2022) 538–545.
[31] J.-H. Lee, J.-H. Yun, J.-S. Han, I.-S.L. Yeo, H.-I. Yoon, Repeatability of intraoral scanners for complete arch scan of partially edentulous dentitions: an in vitro study, J. Clin. Med. 8 (2019) E1187.
[32] H.-S. Oh, Y.-J. Lim, B. Kim, M.-J. Kim, H.-B. Kwon, Y.-W. Baek, Influence of scanning-aid materials on the accuracy and time efficiency of intraoral scanners for full-arch digital scanning: an in vitro study, Materials 14 (2021) 2340.