Impact of the superimposition reference area on intraoral scanning accuracy in a partially dentate maxilla

ABSTRACT

Statement of problem. The alignment of 3-dimensional (3D) files involves selecting a reference area before performing a local best fit alignment during the digital scan superimposition and is essential for comparing digital scans. Scan alignment relies on both reference area location and the alignment algorithm. However, a consensus on the impact of different reference areas on intraoral scanning accuracy is lacking.

Purpose. The purpose of this in vitro study was to assess the impact of 3 superimposition reference areas on the accuracy of 3 intraoral scanners for a partially dentate maxilla.

Material and methods. A Kennedy class II resin cast was scanned using 3 intraoral scanners (Primescan, TRIOS 3, and Emerald) outputting 30 digital scans (10 per scanner). Test scans from intraoral scanners were subsequently compared with a reference digital standard tessellation language file generated by a laboratory scanner with validated accuracy. The files were superimposed using best fit alignment for each intraoral scanner using 3 different superimposition reference areas (whole region of interest, palate, and all teeth). Accuracy was assessed by using a 3D analysis program (Geomagic Control X; 3D systems) for each scanner at 4 preselected areas. Test and reference scan differences were depicted on color maps and quantified via root mean square deviations. Differences were analyzed using regression analysis with the post hoc student *t* test and Bonferroni correction (α=.05).

Results. The TRIOS 3 and Emerald produced positive deviations in the palatal color maps, whereas Primescan produced more uniform color maps, regardless of the superimposition strategy used. Primescan exhibited the best accuracy (trueness and precision) in both palatal and bounded edentulous areas, regardless of the superimposition reference area. The TRIOS 3 recorded the highest distal extension trueness (ranging from 42.9±7.7 µm to 65 ±19.5 µm), and Primescan achieved the highest precision (ranging from 28.5 ±9.8 µm to 48.9 ±16.9 µm), regardless of the superimposition area. Emerald demonstrated the highest teeth trueness (ranging from 31.6 ±6.8 µm to 69.6 ±11.5 µm), while Primescan produced the highest precision (ranging from 17.9 ±6.1 µm to 30.7 ±9.2 µm), regardless of the reference area used.

Conclusions. The chosen reference area for best fit alignment significantly influenced digital scan accuracy ($P<.001$). Primescan displayed the highest palatal and bounded edentulous area accuracy, with TRIOS 3 recording the highest distal extension trueness. Emerald recorded the highest teeth trueness and Primescan recorded the highest distal extension and tooth precision. All conclusions were independent of the superimposition strategy used.

CLINICAL IMPLICATIONS

The precise fit of a prosthesis is highly dependent upon the scan accuracy. This study suggests using the whole cast surface as a reference area for superimposition to assess the accuracy of digital scans.

An accurate intraoral recording is necessary for the production of a well-fitting dental prosthesis, and any errors, particularly at an initial stage, will impair the accuracy of the definitive prosthesis.[1] Recently, removable partial dentures (RPDs) have been constructed using digital scans obtained from intraoral scanners (IOSs).[2] However, the accurate intraoral digital capture of large 3-dimensional (3D) volumes required for partial denture frameworks is challenging, with distortions and inaccuracies commonly observed, particularly with complete arch scans.[3,4] This distortion might be a result of IOSs having small heads, requiring more images to be merged.[3,5] Alternatively, complete arch inaccuracies may result from the lack of distinct anatomic landmarks in the palate and edentulous areas[6] or difficulties in capturing large smooth surfaces because of light reflection.[7-9] These inaccuracies might explain the frequently observed palatal misfit under maxillary major connectors, although evidence to support this is lacking.[10-12] Furthermore, the use of IOSs in distal extension situations has been limited because of difficulties in capturing the physiologic extensions of the movable mucosa, essential for optimal denture base extension.[13,14] Therefore, inherent challenges have been observed in producing well-adapted metal RPD frameworks in the palatal area using digital workflows.[10-12]

According to the International Organization for Standardization (ISO), digital scan accuracy is determined by trueness and precision (ISO standard 5725-1).[15,16] Trueness refers to the extent to which the scanner captures the accurate dimensions of the objects, while precision refers to the reproducibility of the scans.[17-24] An impression's accuracy is currently assessed by superimposing individual test scans utilizing the iterative close point (ICP) algorithm and subtracting linear surface differences, from a reference 3D file. Analysis packages typically display data as color-coded heat maps, indicating differences as relative deviations from the reference data.[17,18,21,24-27] The best fit alignment approach has, however, been criticized for masking the actual errors by minimizing the overall differences in the compared data.[28-30] Factors reported to affect IOS accuracy include scanner selection, dentist expertise, intraoral anatomy, scanning parameters, scanned area, temperature, and lighting conditions.[31-36] Scanning technique, speed, software algorithms, and material properties can also affect accuracy.[24,31,37-41]

The precise selection of a superimposition area is also necessary before comparing two 3D files, since the findings are affected by this choice. Most of the existing research, however, did not identify the superimposition reference area, which is essential for IOS accuracy assessment.[24,42,43] In studies that analyzed movement of the teeth during treatment with a fixed appliance, reliable structures like the palatal rugae have often been used as a reference.[44-47] Researchers analyzing the soft tissue changes have used the teeth as a reliable reference area for best fit alignments.[48] Nevertheless, it cannot be assumed that a landmark is stable and does not change in a digital scan. Selecting stable, reliable areas as references for scan alignment remains challenging, and most previous studies used the whole cast surface for alignment.[17-24] Despite this, research on the accuracy of partially dentate intraoral scans based on the reference area chosen for best fit alignment is lacking. Thus, this study aimed to assess the impact of reference areas used for best fit alignment on the digital scan accuracy of the partially dentate maxilla. The null hypothesis was that the 3 tested reference areas used for best fit alignment would result in statistically similar accuracy of the 3 tested scanners across all evaluation areas.

MATERIAL AND METHODS

A maxillary Kennedy class II modification 1 resin cast was scanned with a desktop scanner (E4; 3Shape A/S) with a reported accuracy of 4 µm. The E4 desktop scanner has been reported to be suitable for generating reference data, eliminating the need to use industrial scanners.[49,50] In this study, the E4 laboratory scanner was determined to have an accuracy of 3.5 ±0.7 µm based on coordinate measuring machine validation (Leitz; Hexagon) (Supplementary Figs. 1 and 2, available online). The same laboratory scanner assessed with a 3D analysis software program (Geomagic Control X; 3D systems) had a precision of 8.5 ±0.7 μm.

The output 3D file was saved as the reference file for subsequent evaluation (RM STL). The study reference cast was then scanned 10 times with 3 different intraoral scanners (Table 1); (Primescan; Dentsply Sirona, TRIOS 3; 3Shape A/S, and Emerald; Planmeca). A summary of the workflow is shown in Figure 1.

Before use, all scanners were calibrated as directed by the manufacturer's guidelines. A single trained investigator (E.N.) performed all scans without powder application, taking a 5-minute rest after every 3 scans to avoid operator fatigue. A consistent scanning environment was maintained by scanning with the dental light off and the windows closed. Approximately 1700 ±100 images were captured during cast scanning (mean scanning time of 78 seconds). Manufacturer-recommended scanning distances and strategies were adhered to (approximately 2 mm from scanner head and tooth surface for Primescan, 0 to 5 mm for TRIOS 3, with green color box indicator for Emerald) as shown in Figure 2. All scans were evaluated for the absence of mesh holes and the presence of all of the cast surface. To assess the trueness and precision of each scan, surface differences were calculated with a 3D analysis software program (Geomagic Control X; 3D Systems). The test and reference scans were aligned by using the software program as a 2-stage process. First, the automatic alignment of scans was carried out, followed by subsequent local best fit alignment using the 3 different reference areas (the whole region of interest (ROI), the palate, and all teeth) (Fig. 1). Then, each test STL file was subtracted from the reference scan (RM STL), and each intraoral scan was evaluated separately for root mean square deviations (RMSDs) in 4 selected areas: the palatal area, distal extension area, bounded edentulous area, and all teeth. To ensure that the same area was selected for each file, an overlay template was created for all files. To determine the alignment registration error, 10 initial and local best fit alignments were performed on 1 file selected from the Primescan group, and the RMS was calculated. The alignment registration error was 0.08 µm. To evaluate trueness for each scanner (Fig. 3), the relative deviation between each of the 10-test digital scans and the RM STL (E4 desktop scanner) was determined for each superimposition strategy. To evaluate precision for each scanner (Fig. 3), the relative deviation was determined between the scan with the best overall trueness (Scan 4) compared with each of the other scans (scans 1 to 10). The RMS deviations in micrometers were determined for the selected regions (palate, bounded edentulous area, distal extension area, and all teeth) for trueness and precision from the generated color maps. For the color maps, scale maximum and minimum limits were set at 0.3 mm with maximum negative deviations (*blue*) and positive deviations (*red*), with *green* indicating fewer deviations.

Statistical analysis of data was performed with a software program (JMP, Version 17 Pro; SAS Institute Inc). A full factorial multiregression analysis was performed for trueness and precision to test the impact of the superimposition strategy, scanner, and evaluated area and their interactions. A student *t* test with Bonferroni corrections was performed for post hoc multiple comparison testing for the interaction between each factor separately (α=.05). A post hoc power analysis was performed, and a power of more than 99% for both trueness and precision determined.

RESULTS

The trueness and precision color map deviations (positive and negative) varied in location based on the superimposition reference areas used (Figs. 4-6). The results of the multiregression analysis revealed that trueness and precision were significantly influenced by the superimposition strategy, scanner, and area, as well as the interaction between all of these factors (P<.001). Nevertheless, the influence of these factors on both trueness and precision was inconsistent (Fig. 7, Tables 2, 3).

Regardless of the reference area, Primescan showed more uniform and homogeneous distributions (green color) of trueness and precision on the color maps than either TRIOS 3 or Emerald. The RMS deviations also indicated that Primescan provided the highest level of palatal trueness and precision of all the scanners tested, regardless of the strategy (Figs 7, 8). Both TRIOS 3 and Emerald showed positive palatal trueness color map deviations, regardless of the superimposition strategy. Nevertheless, Emerald produced more uniform precision distribution color maps than TRIOS 3. Emerald was also consistent with RMS distributions, whereas TRIOS 3 had lower palatal precision (P<.001) than Emerald, regardless of the strategy (Figs. 7, 8, Table 3).

Positive color map deviations were observed in the most distal edentulous areas when the whole ROI and all teeth were used as superimposition reference areas in Primescan. However, when the palate was used as a superimposition reference area, these deviations increased in the last molar tooth, as well as in the most posterior distal extension area. Additionally, both TRIOS 3 and Emerald showed negative deviations at the start scanning point (last molar tooth) and the end scanning point (most distal edentulous area) when the whole ROI and palate were used as reference areas. Emerald, however, displayed fewer positive palatal deviations and more negative distal extension area deviations when the palate was used as a reference area. A detailed analysis of the number, significance, and rank of these deviations can be found in Figures 7 and 8.

The TRIOS 3 scanner had the best RMS trueness values in the distal extension area regardless of the scanning strategy. However, it had the worst precision in the distal extension (*P*<.001) regardless of the strategy. Nonetheless, the trueness values were not significantly different across the strategies based on the post hoc analysis (Tables 2, 3).

With the palate (29.5 ±10 µm) and all the teeth (44.9 ±11.5 µm) as reference areas, Primescan had the best trueness results within the bounded edentulous area, and Emerald had the highest bounded edentulous trueness (29.2 ±9.2 µm) with the entire ROI strategy. Primescan showed the highest precision when the whole ROI (13 ±5.3 µm) and palate (15.3 ±5.9 µm) were used as reference areas.

Primescan had the highest precision for teeth, regardless of the strategy used, Emerald had the highest teeth trueness when the whole ROI (21.6 ±8.6 µm) and all teeth (17.9 ±6.1 µm) were used as reference areas (Tables 2, 3). Finally, all areas had significant differences in accuracy across all strategies (*P*<.001, Tables 2, 3).

DISCUSSION

The reference areas used in this study for superimposition and local best fit alignment significantly affected (*P*<.001) trueness and precision across the 3 scanners tested (Tables 2, 3). Therefore, the null hypothesis that the 3 tested reference areas used for best fit alignment would result in statistically similar accuracy of the 3 tested scanners across all evaluation areas was rejected. The local best fit alignment when used with the iterative closest point (ICP) algorithm influenced both the amount (color map intensity) and location of deviation. The ICP algorithm minimizes differences between superimposed surfaces by selecting the best rigid transformation that aligns the closest points on a surface with those on the other surface.[41] Best fit methods minimize differences between superimposed surfaces by considering fixed structures as references, a factor that differs among tested strategies. All scanners had the lowest deviations in the palatal region when the palate was used as the superimposition reference area (Figs. 7, 8). The lowest deviations in the palatal region could be attributed to the local best fit method, which minimizes differences while considering the palate as a stable structure.[41] However, when both the whole ROI and all teeth were used as stable reference areas, the palate had higher deviations in all scanners than when the palate was used as a fixed landmark. This local best fit caused shifting deviation in the palatal area, thereby increasing overall deviations. The results suggested that no definitive conclusion can be drawn regarding the superiority of reference areas for alignment. Hence, the entire ROI should be used for local best fit alignment when assessing intraoral scans.[25,26]

Regardless of the superimposition reference areas, both the TRIOS 3 and Emerald had higher palatal deviations than those of the Primescan (Figs. 7, 8). The higher palatal deviations aligned with the color map deviation patterns, as TRIOS 3 and Emerald displayed positive palatal deviations, while Primescan had minimal deviations (*green* color). These variations may be associated with the distinct data capture principles of the 3 scanners. Primescan uses photographs and videos for data acquisition by utilizing dynamic deep scan technology compared with TRIOS 3, which uses photographs employing confocal microscopy technology, while Emerald is a video-based scanner that uses projected pattern triangulation (Table 1). The different imaging technologies might influence the scanner’s 3-dimensional accuracy, although strong clear data that favor one technology over another is lacking. Scanners are also known to vary in accuracy because of hardware and software components, with upgrades in software resulting in improvements in transfer accuracy, especially in the latest IOS versions.[21,38] However, scanning the palate remains challenging, as both TRIOS 3 and Emerald scans had higher palatal deviations than Primescan.

The deviations (positive and negative) of color maps for both trueness and precision were substantial at both the start and end scan points. The lack of trueness and precision could be attributed to stitching errors observed in the first and last images. The study results aligned with previous research testing the same scanners, indicating higher deviations in the distal segments of the cast and in the molar area (scanning start point) for TRIOS and Primescan.[35,36,40] The scanning sequence strategy has been shown to significantly impact intraoral scanner accuracy and represents an additional accuracy dependent factor.[40] All tested scanners, particularly TRIOS 3 and Emerald, had a similar deviation pattern. In clinical practice, the scanning sequence may be important in complete arch scan accuracy, particularly with scanners known to have sequence dependent accuracy variations.

The TRIOS 3 and Emerald scanners showed higher trueness deviations in the palate and distal extension areas, regardless of the superimposition strategy (Figs. 7, 8; Tables 2, 3). These deviations may be attributed to the challenge of stitching relatively smooth, large palatal, and distal extension areas, which are more easily misaligned compared with scanning a region with a more detailed shape.[4,37] In addition, distal extension deviation values were consistently higher than those in bounded edentulous regions for all scanners, regardless of the strategy. Previous studies have reported similar stitching inaccuracies in smooth extended edentulous areas possibly because of the absence of teeth or other reference landmarks.[6,42] Regardless of the superimposition area, TRIOS 3 had the highest trueness for the distal extension (from 42.9 ±7.7 µm to 65 ±19.5 µm), while Primescan had the highest precision (from 28.5 ±9.8 µm to 48.9 ±16.9 µm). The optimal trueness values for partially dentate digital scans were identified in the posterior arch region at 21.9 ±1.5 µm,[18] which was lower than the trueness value for the distal extension recorded in this study. The differences between the studies could be associated with variations in scanning, software versions, or superimposition strategies.

All scanners had higher deviation values in the dentate region as compared with the bounded edentulous areas, regardless of the superimposition strategy (Figs. 7, 8). Stitching errors may also occur more frequently in dentate regions, particularly anteriorly since the scanner heads are small, [30,36,38] necessitating the stitching of multiple captured images and increasing the risk of misalignment.[8,19,20,27] Another factor contributing to the decreased accuracy in the dentate area is the anatomic complexity of tooth surfaces (such as cuspal inclinations, fissure depth, and anterior tooth curvature).[33] The zigzag pattern used in this study to scan the anterior teeth may also result in alignment and stitching errors. Linear scanning has been shown to yield more accurate results for anterior teeth than for posterior teeth.[34] However, further research is required to confirm these findings.

In evaluating intraoral scan accuracy and acceptable deviation, it is important to consider the displacement of the oral tissues and whether the denture is mucosal, tooth-supported, or a combination of both. In the fabrication of RPDs, a tolerance range of 90 to 240 µm has been defined for tooth-supported frameworks based on the thickness of the periodontal ligament.[51,52] Tolerance ranges of up to 300 µm for distal extension dentures have been specified, based on the mucosal displacement of the denture toward the soft tissue.[53] In the current study, the trueness for all scanners ranged from 20.9 ±3.9 to 113.5 ±15.8 µm, and precision ranged from 17.9 ±6.1 to 88.7 ±20.4 µm, regardless of the evaluated area, values that were within the clinical tolerance range.

Limitations of the study included the in vitro scanning of resin casts compared with direct scanning of the oral cavity because of the translucency and refraction differences of resin casts compared with anatomic tissues. However, an advantage of in vitro resin cast scanning is the absolute control of saliva or blood and soft tissue mobility, which can influence scan accuracy. Clinical studies are required to determine whether the conclusions drawn here are translatable to the oral environment.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The choice of the reference area for best fit alignment significantly impacts the digital scan accuracy of the tested scanners (P<.001).
2. Regardless of the superimposition strategy used, scans of the palate were associated with low levels of accuracy in both the TRIOS 3 and Emerald scanners.
3. Primescan recorded the highest accuracy (trueness and precision) in palatal and bounded edentulous areas and the highest precision for distal extension and teeth, regardless of the superimposition reference area. The TRIOS 3 had the highest distal extension trueness, while the Emerald showed the best tooth precision across all superimposition reference areas.

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TABLES

Table 1. Manufacturers' specifications for scanners used

Scanner	Manufacturer	Software version	Scanning technology	Acquisition
Primescan	Dentsply Sirona	5.1.1.	Dynamic Deep Scanning	Photograph and video-based scanner
TRIOS 3	3Shape A/S	20.1.2.	Confocal microscopy	Photograph based scanner
Emerald	Planmeca	6.0.1.	Projected pattern triangulation	Video based-scanner

Table 2. Post hoc student *t* test with Bonferroni correction (α=.000079) representing trueness values for interactions between strategy, scanner, and area. Least square (Sq) mean differences and standard (Std) error also presented. Levels not connected by same letter significantly different. AT, all teeth superimposition strategy; B, bounded edentulous area; DE, distal extension; EM, Emerald; P, palatal area; PL, palate as superimposition reference area; PS, Primescan; T, all teeth area; T3, TRIOS 3; W ROI, whole region of interest strategy.

Level (strategy, scanner, area)	Connecting letters (A to L)	Least Sq Mean	Std Error
PL, EM, F	A	113.54	4.50
AT, EM, P	A B	97.16	4.50
PL, T3, T	A B	96.96	4.50
AT, T3, P	B C	86.03	4.50
PL, PS, DE	B C D	84.72	4.50
AT, PS, DE	B C D E	76.78	4.50
PL, EM, T	C D E F	69.56	4.50
AT, T3, B	C D E F G	66.52	4.50
AT, T3, DE	C D E F G H	65.02	4.50
W ROI, PS, DE	C D E F G H	61.89	4.50
W ROI, T3, T	D E F G H	60.58	4.50
AT, EM, DE	E F G H	59.22	4.75
PL, EM, B	E F G H	58.60	4.50
W ROI, T3, P	E F G H	57.84	4.50
W ROI, T3, B	E F G H	56.67	4.50
W ROI, EM, P	E F G H I	55.49	4.50
PL, T3, DE	E F G H I	55.46	4.50
AT, T3, T	E F G H I J	54.52	4.50
PL, T3, B	E F G H I J K	53.57	4.50
PL, PS, T	E F G H I J K	52.84	4.50
W ROI, EM, DE	F G H I J K L	47.21	4.50
W ROI, PS, T	F G H I J K L	47.12	4.50
PL, T3, P	F G H I J K L	47.05	4.50
AT, EM, B	F G H I J K L	45.20	4.50
PL, EM, P	F G H I J K L	45.03	4.50
AT, PS, B	G H I J K L	44.88	4.50
W ROI, EM, T	G H I J K L	44.68	4.50
W ROI, T3, DE	G H I J K L	42.92	4.50
AT, PS, P	H I J K L	41.64	4.50
AT, PS, T	H I J K L	41.17	4.50
AT, EM, T	I J K L	31.56	4.50
W ROI, PS, P	I J K L	31.33	4.50

Level (strategy, scanner, area)	Connecting letters (A to L)			Least Sq Mean	Std Error
W ROI, PS, B	J	K	L	30.86	4.50
PL, PS, B		K	L	29.54	4.50
W ROI, EM, B		K	L	29.15	4.50
PL, PS, P			L	25.73	4.50

Table 3. Post hoc student *t* test with Bonferroni correction (α=.000079) representing precision values for interactions between strategy, scanner, and area. Least square (Sq) mean differences and standard (Std) error also presented. Levels not connected by same letter significantly different. AT, all teeth superimposition strategy; B, bounded edentulous area; DE, distal extension; EM, Emerald; P, palatal area; PL, palate as superimposition reference area; PS, Primescan; T, all teeth area; T3, TRIOS 3; W ROI, whole region of interest strategy.

Level (strategy, scanner, area)	Connecting letters (A to K)											Least Sq Mean	Std Error
PL, T3, DE	A											95.03	3.71
AT, T3, P	A											88.69	3.71
AT, T3, DE	A											88.16	3.71
PL, T3, T		B										59.70	3.71
W ROI, T3, P		B	C									50.49	3.71
PL, PS, DE		B	C	D								48.94	3.71
PL, T3, B		B	C	D	E							45.43	3.71
PL, EM, T		B	C	D	E	F						44.36	3.71
AT, EM, DE		B	C	D	E	F	G					43.59	3.93
PL, EM, DE		B	C	D	E	F	G	H				40.76	3.71
AT, EM, P			C	D	E	F	G	H	I			37.18	3.71
W ROI, T3, DE			C	D	E	F	G	H	I	J		34.13	3.71
AT, PS, P			C	D	E	F	G	H	I	J		33.92	3.71
W ROI, EM, DE			C	D	E	F	G	H	I	J		33.52	3.71
PL, PS, T			C	D	E	F	G	H	I	J	K	30.68	3.71
W ROI, T3, T			C	D	E	F	G	H	I	J	K	30.51	3.71
W ROI, EM, T				D	E	F	G	H	I	J	K	30.08	3.71
W ROI, PS, DE				D	E	F	G	H	I	J	K	29.54	3.71
AT, PS, DE					E	F	G	H	I	J	K	28.54	3.71
PL, EM, B					E	F	G	H	I	J	K	28.04	3.71
PL, T3, P					E	F	G	H	I	J	K	27.21	3.71
AT, EM, B					E	F	G	H	I	J	K	26.21	3.71
AT, EM, T					E	F	G	H	I	J	K	25.89	3.71
AT, T3, T						F	G	H	I	J	K	24.16	3.71
W ROI, EM, B							G	H	I	J	K	23.72	3.71
AT, PS, B							G	H	I	J	K	23.20	3.71
W ROI, EM, P							G	H	I	J	K	22.69	3.71
W ROI, PS, T								H	I	J	K	21.59	3.71
W ROI, T3, B								H	I	J	K	21.57	3.71
W ROI, PS, P								H	I	J	K	21.20	3.71
AT, T3, B								H	I	J	K	20.87	3.71
PL, EM, P									I	J	K	19.91	3.71

Level (strategy, scanner, area)	Connecting letters (A to K)			Least Sq Mean	Std Error
AT, PS, T	I	J	K	17.90	3.71
PL, PS, P	I	J	K	17.34	3.71
PL, PS, B		J	K	15.32	3.71
W ROI, PS, B			K	13.02	3.71

FIGURES

Figure 1. Study workflow.

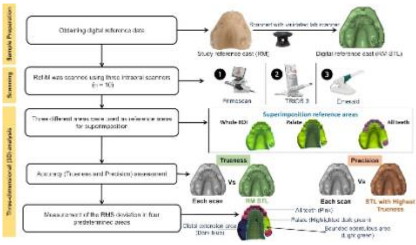


Figure 2. Scanning strategy for all scanners. Each circle represents start point of each side, and each arrow represents end point. Arrows with numbers indicate direction and sequence of scanning process.

Figure 3. Study assessment parameters used for accuracy (trueness and precision). Left section shows trueness evaluation, and right section shows precision evaluation. Testing trueness of each digital scan involved superimposing with reference cast scan (RM STL). Precision evaluated by superimposing test scan with highest trueness level (STL no.4) with all other scans within same group. STL, standard tessellation language.

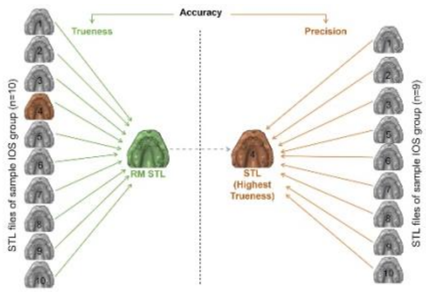


Figure 4. Color map analysis of three scanners; Primescan, TRIOS 3, and Emerald, with entire region of interest (ROI) as superimposition reference area. Scale adjusted to 0.3 mm in both negative and positive directions. *Green*: fewest deviations. *Blue*: negative deviations. *Yellow* to *red*: positive deviations. For trueness evaluation, each test scan compared with reference digital file (RM STL), and, for precision, compared with scan with highest degree of trueness. STL, standard tessellation language.

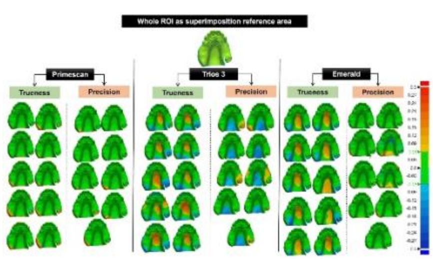


Figure 5. Color map analysis of three scanners; Primescan, TRIOS 3, and Emerald, with palate as superimposition reference area. Scale adjusted to 0.3 mm in both negative and positive directions. *Green*: fewest deviations. *Blue*: negative deviations. *Yellow to red*: positive deviations. For trueness evaluation, each test scan compared with reference digital file (RM STL), and, for precision, compared with scan with highest degree of trueness. STL, standard tessellation language.

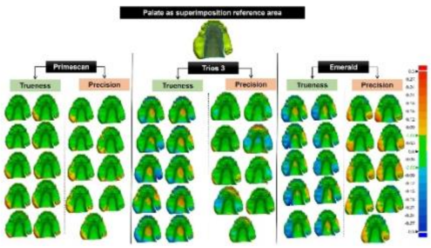


Figure 6. Color map analysis of three scanners; Primescan, TRIOS 3, and Emerald, with all teeth as superimposition reference area. Scale adjusted to 0.3 mm in both negative and positive directions. *Green*: fewest deviations. *Blue*: negative deviations. *Yellow to red*: positive deviations. For trueness evaluation, each test scan compared with reference digital file (RM STL), and, for precision, compared with scan with highest degree of trueness. STL, standard tessellation language.

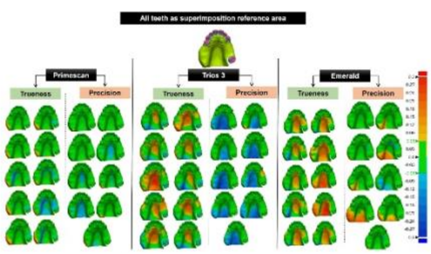
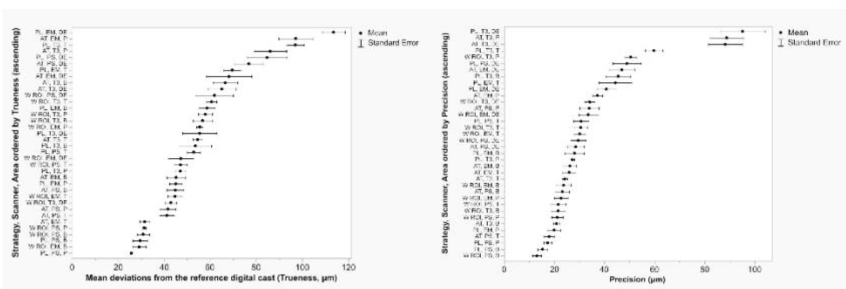


Figure 7. Interactions between strategy, scanner, and area. Having all interactions between tested factors, trueness values ranked in ascending order. Y axis presents strategy, scanner, and area, where first abbreviation represents strategy, second abbreviation represents scanner, and third abbreviation represents area. A, Mean trueness values. B, Mean precision values.

AT, all teeth superimposition strategy; B, bounded edentulous area; EM, Emerald; DE, distal extension area; P, palatal area; PL, palate as superimposition reference area; PS, Primescan; T, all teeth area; T3, TRIOS 3; W ROI, whole region of interest strategy. Error bars constructed using one standard error from mean.

A  B

SUPPLEMENTARY MATERIALS

Supplementary Material 1. Justification for inclusion of Supplementary Figures

Two supplementary figures included to summarize the coordinate measurement analysis (Supplementary Figure 1, available online) of laboratory scanner accuracy based on center distance measurements of ceramic spheres attached to study cast utilizing both random and systematic errors assessments. In Supplementary Figure 2 (available online), second illustration summarizes 3D assessment of laboratory scanner precision based on three local best fit alignment reference areas.

SUPPLEMENTARY FIGURES

Supplementary Figure 1. Flowchart illustrating procedures used for accuracy validation of the laboratory scanner by using a coordinate measuring machine (Leitz; Hexagon) as reference device providing nominated true values. CMM: coordinate measuring machine.

Supplementary Figure 2. Flowchart illustrating procedures used for precision validation of laboratory scanner (E4; 3Shape A/S) by using 3D surface analysis software. Study cast scanned ten times, superimposing each scan on another by using three different areas to align scans according to best local fit. Scan precision determined by measuring root mean square (RMS) deviations throughout entire region of interest. Precision of the scanner was 8.5±0.7 µm.