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Full arch precision of six intraoral scanners *in vitro*

C.A. Osnes[a,b,*], J.H. Wu[c], P. Venezia[d], M. Ferrari[e,f], A.J. Keeling[a]

[a] Department of Restorative Dentistry, School of Dentistry, University of Leeds, Leeds, United Kingdom
[b] Department of Medical Biotechnologies, University of Siena, Siena, Italy
[c] School of Dentistry, University of Leeds, Leeds, United Kingdom
[d] Department of Prosthodontics, School of Dental Medicine, University of Catania, Catania, Italy
[e] Department of Prosthodontics & Dental Materials, School of Dental Medicine, University of Siena, Siena, Italy
[f] Dental Trial Clinical Research Unit [DenTCRU], School of Dentistry, University of Leeds, Leeds, United Kingdom

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ABSTRACT

Purpose: Intraoral scanners may offer an alternative to traditional impressions. That intraoral scanners produce precise scans is essential. Popular methods used to evaluate precision tend to rely on mean distance deviation between repeated scans. Mean value measurements may underestimate errors resulting in misleading conclusions and clinical decisions. This study investigated the precision of six intraoral scanners using the traditional method of measuring mean error, and a proposed method considering only the most extreme and clinically relevant aspects of a scan.
Methods: An edentulous model was scanned five times using six intraoral scanners. The repeated scans were aligned, uniformly trimmed and mean surface deviation measured across all 20 scan combinations within each scanner group. All scan combinations were then measured by arranging scan vertices from greatest to smallest unsigned distance from its compared scan and measuring the median value within the 1% of most greatly deviating points. Traditional mean deviation results and upper-bound deviations were compared.
Results: The upper-bound deviation within a scan reported errors up to two times greater than those found when measuring global mean distances. Results revealed clinically relevant errors of more than 0.3 mm in scans produced by the Planmeca and Dentalwings scanners, findings not seen when measuring mean distance error of the complete scan.
Conclusions: Upper-bound deviation of a cropped scan may provide a clinically useful metric for scanner precision. The Aadva, 3Shape, CEREC and TDS produced scans potentially appropriate for clinical use while Planmeca and Dentalwings produced deviations greater than 0.3 mm when measuring the upper-bound deviation.

1. Introduction

Replacing traditional impressions and models with digital scans offer potential benefits for dental practitioners and patients. Previous studies have shown that digital scanners reduce the cost of storing and transporting impressions, and may also be preferred by patients [1]. That a scanner produces precise and true virtual models is key.

Much work has been undertaken to validate the trueness and precision of intraoral scanners (IOSs). Precision, defined as the variability of repeated measurements, is commonly used when the real measurement value (trueness) is difficult to ascertain. Recent reviews show a tendency for digital impressions to be precise over short distances, but to fall short of their physical counterparts over larger arch spans [2,3]. Ahlholm et al. [4] report that IOSs may result in acceptable scans when recording a single or partial fixed dental prosthesis preparation. Ender et al. [5] found IOSs to be capable of recording clinically satisfactory quadrant impressions. Both Ender et al. and Ahlholm et al. found a significant difference in accuracy between traditional and digital impressions of full arches: digital impressions being less precise than high precision traditional materials. Ahlholm et al. conclude with the recommendation of the continued use of traditional impression techniques for full-arch impressions.

Nevertheless, recent attention has been directed towards the challenges surrounding edentulous scanning using IOSs. These include difficulties in recording muco-compressive impressions

* Corresponding author at: School of Dentistry, University of Leeds, Leeds LS2 9JT, United Kingdom.
E-mail address: C.A.Osnes@leeds.ac.uk (C.A. Osnes).

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and functional depth and width of sulci, and the lack of interesting topology in edentulous regions causing cumulative errors in the stitching process of data during scanning [6]. Suggestions to add features clinically (such as painting pressure indicating paste or adding composite spheres to the mucosa [7–9]) have been shown to help in recording a digital impression, but this is arguably no longer a true impression of the patient; and could be construed as flawed attempts to try and fit digital technology to a purpose for which other techniques might be more appropriate.

With the high rate of development within digital solutions, and as manufacturers respond to clinical requirements, software updates may improve data acquisition methods and stitching processes, calling for ever newer investigations.

However, the handling and analysis of the data extracted from, and for, scan comparisons vary within the literature. A key challenge is to distinguish between methodology-induced noise and valid, but erroneous, data. Another is to determine the threshold at which an error is clinically significant. There is a lack of agreement of clinically relevant metrics by which to compare three-dimensional [3D] data within the dental field which could benefit from further investigation.

A common metric for precision is the mean distance deviation between scan-pairs. This method requires caution as data typically contains many thousands of points, and scan alignment algorithms serve solely to minimise the mean distance between two sets of such points (regardless of clinical fit). This phenomenon has been reported to result in the underestimation of tooth wear when standard alignment methods are used [10]. Even if the alignment was perfect, the resulting regression to the mean of such large datasets can underestimate clinically relevant errors when using mean distance deviations. Small areas of significant inaccuracy (such as at a crown margin or an overextended sulcus) can be 'drowned out' by large regions of accurate smooth surface alignment [11].

Several studies specify a confidence interval and perform all analysis on the data within this envelope, on the assumption that this will remove erroneous data (scanner noise) and retain valid scan data. Some investigators remove as much as the maximum and minimum 10% before analysis. Since 3D data from a scanner has already undergone statistical outlier removal before surfacing it may be counterproductive to remove such large quantities of potentially valid data and further compound the regression to the mean problem [5,12]. In summary, while maximum value removal excludes noise and outliers from the analysis, it may also exclude valid data; disregarding that the greatest true error in a scan can be of great clinical relevance.

The issue of relying on confidence intervals has been discussed previously [13]. In some cases, methods may allow for scan data to be consistently pruned or cropped to eliminate scan noise prior to analysis. Based on this premise, some investigators have chosen to analyse all data points, as opposed to applying a confidence interval [13–15]. In the case of the 2013 study evaluating 'uncropped' data, findings were reported to show similar results to a cited study which relied on a "80–20 percentile method." This is to be expected when comparing mean distance deviation, as discussed above, with mean values potentially drowning out clinically relevant differences.

This paper compares the precision of six IOSs in scanning a replica edentulous maxillary arch. An edentulous model was used as it is likely to provide a challenge for IOSs in terms of smooth anatomy. Precision was assessed first by measuring conventional signed mean deviations over the full surface. The unsigned median error over the poorest 1% of the surface was then assessed to determine whether this data was likely to be scanner noise, or valid data. The surface area that this 1% represents on the scanned model was calculated, to assess its clinical relevance.

1.1. Null hypotheses

(A) That there are no significant differences between the precision of edentulous scans using six different intraoral scanners when assessed using standard signed mean deviation.
(B) That there are no significant differences between the precision of edentulous scans using six different intraoral scanners when assessed using the poorest fitting 1% unsigned median deviation.
(C) That there are no significant differences in the clinical acceptability of each scanner under both analyses, when considering a threshold of <0.3 mm as a clinically acceptable error.

2. Materials and methods

A metal edentulous model was scanned by the same operator using six different intraoral scanners, namely: True Definition Scanner [*TDS*] SW 5.1.1 (3M, Maplewood, MN, USA), *Planmeca* Emerald SW 4.6 (Planmeca, Helsinki, Finland), *Omnicam* SW 4.5.2 (Sirona, now Dentsply Sirona, York, PA, United States), Straumann Cares Intraoral Scanner, previously Dental Wings [*DWIO],* SW 2.1 (Straumann, Basel, Switzerland), TRIOS Model s1P, SW 1.4.7.5 (*3Shape,* Copenhagen, Denmark), and *Aadva* iOS100 (GC Corp., Tokyo, Japan). Each scan was repeated five times and exported as Stereolithography [stl] files. All scans were aligned into a common coordinate frame with custom alignment software using the Generalized Iterative Closest Point (GICP) algorithm [16] which has been shown to be more robust than standard ICP; the implementation used was adapted from the PointCloudLibrary [17].

The first scan from each of the six scanners were all aligned. The four subsequent repeat scans were then aligned to the first scan within each group and mesh distances measured as detailed below. This process was repeated using the second, third, fourth and fifth scan as the 'base scan' for all scan sets, resulting in 20 possible combinations per scanner, and a total of 120 alignments over all six scanners.

To measure the surface deviations, a custom set of trimming planes were created and applied to all scans; this ensured that all scans were cropped identically, retaining only the clinically relevant surface extending to the functional depth and width of the sulcus and to the post dam region. This plane crop method trimmed through triangles of the mesh to prevent artificially induced errors caused by removing entire edge triangles. The mean surface area of the individual trimmed scan, and the mean surface area of each scan group, was calculated using Meshlab [18], so that the magnitude of 1% of the surface area could be determined.

The scanning precision of each test group was assessed by two methods. Firstly, by measuring the signed mean surface deviation between each pair of scans, and the signed standard deviations between each scan-pair within an IOS group. The mean values for these metrics, over the 20 alignment pairs, were reported for each group. Secondly, the 1% of vertices which deviated by the largest unsigned amount were identified. For each scan-pair, these unsigned deviations were ranked and plotted to identify signs of noise (extreme or erratic errors) versus genuine erroneous data (smoothly decreasing errors). The median error value of these poorest 1% was noted to be clearly within 'valid' data for each scanner and was recorded for each alignment [referred to *as the upper-bound deviation* from here on]. The results from each comparison method were compared across scanners using one-way ANOVA and Multiple Comparisons with Bonferroni correction.

The agreement between scanners was then tested by aligning and measuring all possible scan combinations across the six groups. This led to 25 separate alignments per group-pair (*e.g.*

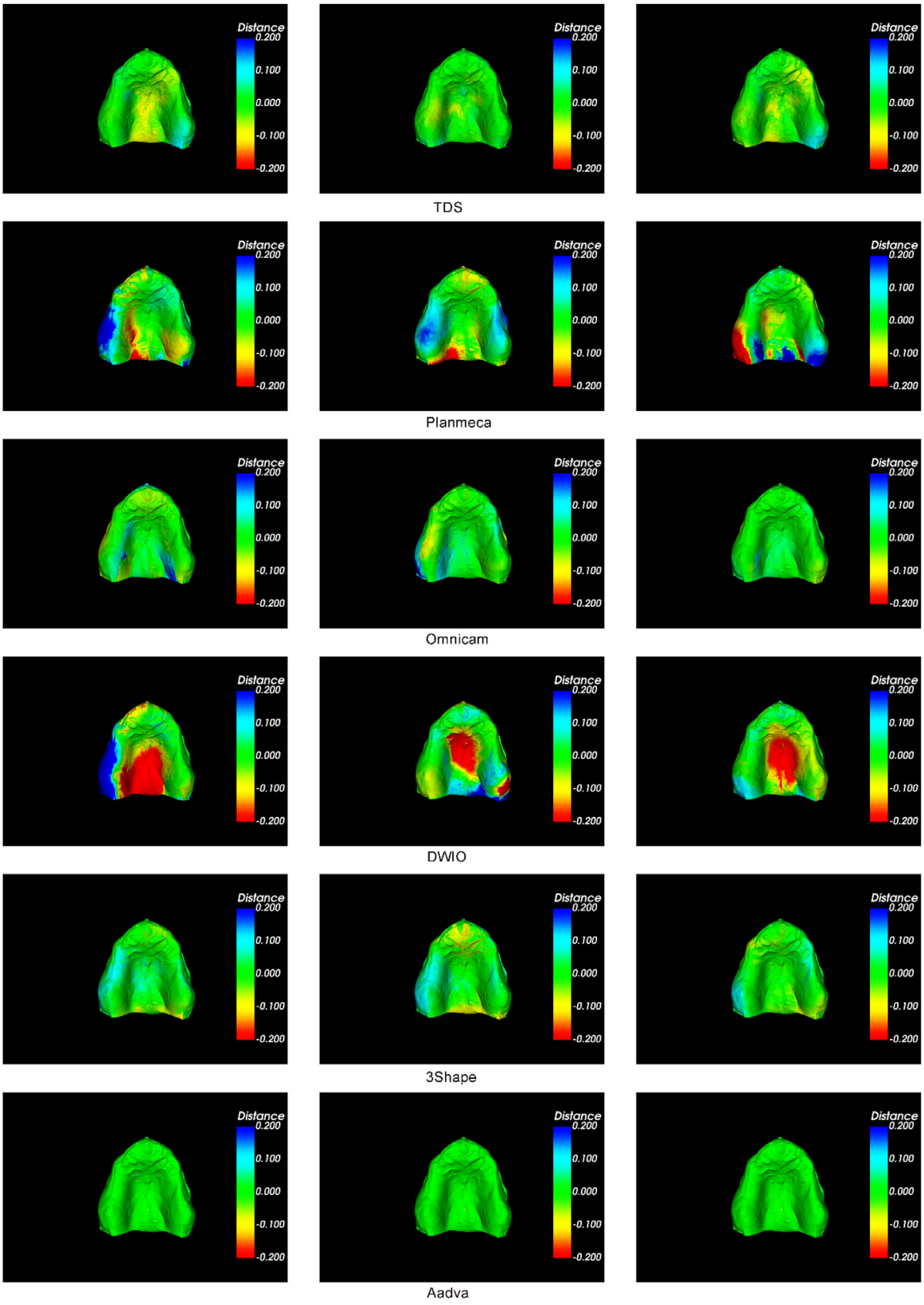

Fig. 1. Colormap showing (from left to right) 2nd, 3rd and 4th scan compared to the 1st scan for each scanner, with distance measured in millimeters.

Planmeca 1–5 to Trios 1–5), and 30 possible group pairings; 750 alignments in total. The upper-bound deviation was recorded for each group-pair. The normality of deviation was evaluated by Kolmogorov–Smirnov test and the homoscedasticity was assessed by Levene's test. One-way ANOVA was used to assess the difference in mean deviation among the group-pairs, and Bonferroni correction was applied to *post hoc* multiple pairwise comparisons.

Statistical significance was defined as $p < 0.05$ in all cases.

Table 1. Global positive and negative mean for each scanner, see results plotted in Fig. 2.

Global positive and negative mean (mm) for each scanner				
	Mean pos. (SD)	Mean neg. (SD)	Pos. mean SD	Neg. mean SD
TDS	0.025 (0.005)	−0.025 (0.005)	0.02	0.02
Planmeca	0.087 (0.034)	−0.084 (0.031)	0.098	0.092
Omnicam	0.032 (0.011)	−0.031 (0.011)	0.028	0.028
DWIO	0.097 (0.038)	−0.096 (0.039)	0.093	0.091
3Shape	0.026 (0.005)	−0.026 (0.005)	0.019	0.019
Aadva	0.003 (0.001)	−0.003 (0.001)	0.007	0.005

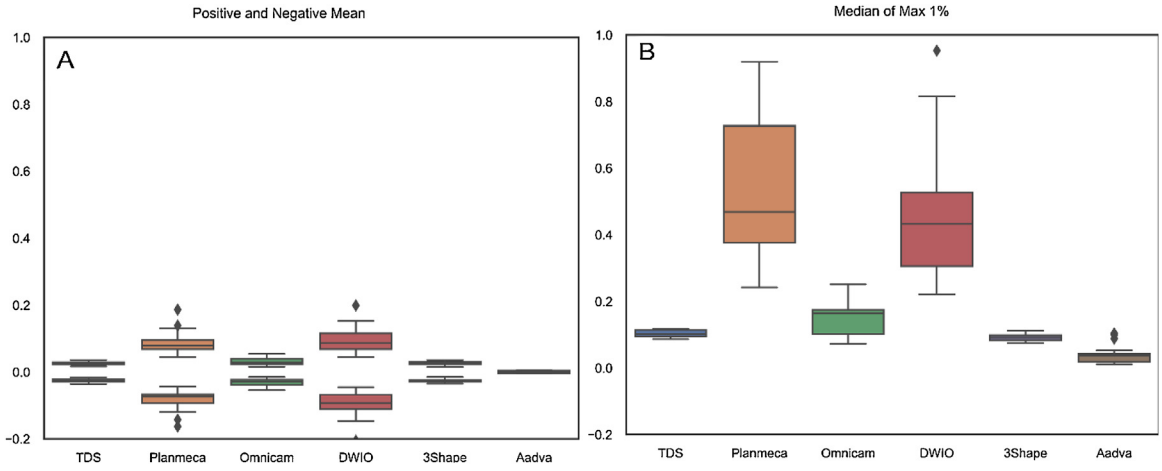

Fig. 2. (A) Global positive and negative mean for each scanner. The line indicates mean value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond. (B) Median of greatest 1%. Distance in millimeters. The line indicates mean value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond. All distances in millimeters.

3. Results

The mean surface area of the trimmed model was 3753 ± 16.9 mm^2. Therefore, 1% of the vertices represented approximately 37.5 ± 0.17 mm^2.

Figure 1 shows colormaps of the trimmed surface deviation comparisons for representative samples from each scanner group. Aadva consistently displayed the lowest deviations while DWIO and Planmeca showed the largest. Mean positive and negative surface deviations remained below 100 μm for all scanners as did standard deviations for individual scans. Table 1 shows global positive and negative mean deviations, and positive and negative standard deviations for all scanners. Kolmogorov–Smirnov test showed that the normality of the deviation measures was not violated. Levene's test indicated that the variances among scanners or group-pairs were not equal, but one-way ANOVA was still used because the sample size among groups was equal and the impact of unequal variances on the results was very small.

Global positive and negative mean distances with standard deviations have been plotted in Fig. 2A. Fig. 3 shows the ranked unsigned deviations for the poorest fitting 1% of vertices for each scanner. In all cases, disproportionately larger errors were noted for only the first small fraction of vertices — less than one tenth of the total 1% sample. This is indicated by the "L"— shaped descent of the poorest fitting vertices. The number of vertices comprising 1% of the scan varied between scanners, ranging from approximately 900 for *DWIO* up to 2000 for TDS. The mean distance of the medians of the poorest fitting 1% of vertices were: 0.103 mm (TDS), 0.531 mm (Planmeca), 0.153 mm (Omnicam), 0.452 mm (DWIO), 0.092 mm (3Shape), 0.040 mm (Aadva); these are plotted with standard deviations in Fig. 2B. These errors exceeded 0.3 mm in two groups; DWIO (0.45 ± 0.19 mm) and Planmeca (0.53 ± 0.21 mm).

The comparisons across IOSs, as given by median of poorest 1% of vertices, are reported in Table 2.

4. Discussion

This study investigated the precision of different IOSs using two measurement methods *in vitro*.

There was a significant difference between some scanners investigated when assessing repeated scan precision using both the signed mean deviation method and the upper-bound deviation method. While the upper-bound deviation reported that the Planmeca and DWIO scanners exceeded the threshold of <0.3 mm, these findings were not seen using the standard signed mean deviation. Thus, all null hypotheses were rejected.

Several studies demonstrate that intraoral scanning *in vivo* reduces scan accuracy due to movement restrictions and the optically challenging environment within the oral cavity. Results obtained *in vitro* can therefore be assumed to be an optimal scenario and real-world clinical precision may be lower [11,19,20].

Despite the varying number of points produced per mesh from each scanner, the automated crop method used for this study resulted in a similar surface area for each scan (mean surface area 3753 ± 16.9 mm^2) as expected. This indicates that the alignment and cropping tools used are unlikely to have had much, if any, unfavorable effect on the total scan volume data prior to measurement, as this would likely have been reflected by greater variability in mesh surface area. However, a small scan/alignment error could conceivably have a disproportionate effect on the largest surface deviations following cropping. For example, a vertical surface that just missed a cropping plane in one model, but was just included in another, might produce a few very large error distances. For this reason, all the errors in the poorest 1% (Fig. 3) were visually assessed to exclude any apparent outliers. An

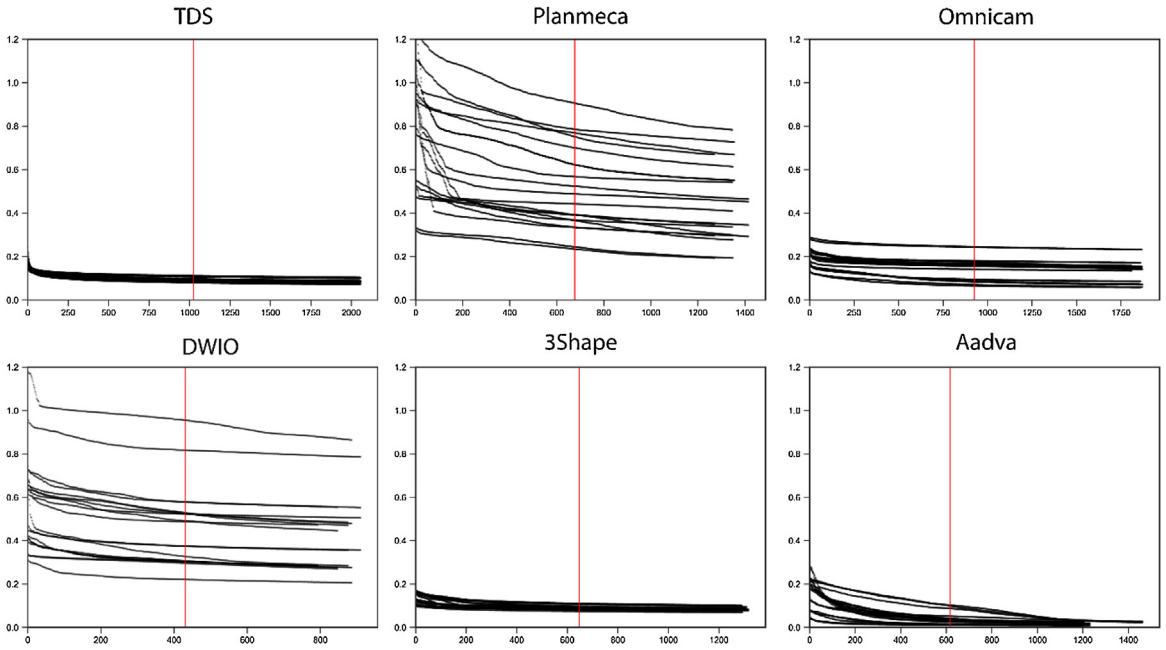

Fig. 3. Maximum 1% of each scan-pair measurement plotted. Y axis ranges from 0 to 1.2 mm. Vertical red line indicates median point.

Table 2. Comparison between the upper-bound deviation (mm) (median value of most greatly deviating 1% of each scan) across all scanners based on all 750 scan combinations. *Note*: p-value represents the overall significance between scanners for a given model. *Denotes statistical significance at the 0.05 level with *post hoc* Bonferroni correction.

Upper-bound deviations (mm) compared across all scanners							
	TDS	Planmeca	Omnicam	DWIO	3Shape	Aadva	p-Value
TDS		0.44 (0.20)	0.31 (0.05)*	1.15 (0.27)*	0.5 (0.1)*	0.26 (0.03)*	<0.001
Planmeca	0.39 (0.17)		0.40 (0.13)*	0.80 (0.25)*	0.48 (0.12)*	0.31 (0.13)*	<0.001
Omnicam	0.31 (0.04)*	0.41 (0.15)*		0.69 (0.20)*	0.15 (0.04)*	0.11 (0.04)*	<0.001
DWIO	1.16 (0.18)*	0.80 (0.25)*	0.70 (0.19)*		0.69 (0.18)*	0.77 (0.22)*	<0.001
3Shape	0.48 (0.09)*	0.50 (0.14)*	0.15 (0.05)*	0.65 (0.16)*		0.15 (0.01)*	<0.001
Aadva	0.26 (0.03)*	0.32 (0.14)*	0.12 (0.04)*	0.76 (0.22)*	0.16 (0.01)*		<0.001

alternative would be to always compare the cropped source surface against a full version of the target mesh.

The current study specified that an error greater than 0.3 mm at the 99.5% most deviating aspect of the scan would be considered likely to have a clinical impact. The exact percentage value would depend on the surface area of the scan and the intended clinical procedure. Errors below a maximum of 0.2 mm have previously been reported as clinically acceptable for complete dentures [21]. More recently, deviations in the posterior region of maxillary and mandibular dentures when flasked traditionally approached 0.25 mm [22]. Errors of 0.3 mm can therefore be considered to be clinically relevant and inferior to current standard practice.

Signed mean distance measurements revealed that Aadva produced the most precise data, with statistically significant signed mean differences compared to all other scanners tested. The signed standard deviation of the Aadva was only significant compared to Planmeca and DWIO. This low mean deviation may be an indication towards the underlying algorithm used during data collection: a centre-of-voxel-based point-set simplification algorithm might create datasets with minimal variation across scan repetitions. While the precision of resulting scans is high, the trueness of a scanner using such an algorithm, impetuously, is questionable. However, trueness validation is beyond the scope of this study. Interestingly, the plotted max 1% points illustrated greater variation between Aadva scans than the 3Shape and TDS (Fig. 3), suggesting more greatly deviating outliers, and hence a reduced precision by the Aadva than that suggested by the global mean values. Empirically, the Aadva scans appeared 'simplified', *i.e.* lacking surface detail, which may also imply an algorithm which collects the regional mean of multiple vertices. This would increase the precision but reduce the resolution (the ability to discern fine detail), in the same way that a medium bodied silicone impression might be precise, but not reveal the fine detail of a light-bodied wash.

Much less than the greatest 0.5% of the data appeared to be spurious (Fig. 3). It was decided that the median of the greatest 1% of points, over the 20 comparisons for each scanner would be a safe indicator of the clinically relevant deviation produced by each scanner, albeit a likely underestimate of the real value. Plotting the first percent of the greatest error of each scan gave a clear indication of both the proportion of noise in the scan and the greatest error within the scan. In this experiment, 1% of the scan object was estimated to represent a cumulative surface area of 37.5 $\pm$ 0.17 mm^2. This is equivalent to more than a 6 mm $\times$ 6 mm patch, larger than the occlusal surface of a premolar if all erroneous points were to be located within close proximity, and potentially clinically relevant.

While scanner trueness is beyond the scope of this study, comparing the variation between scanners may give an indication of trueness if several scanners reach similar conclusions. Whilst there were statistically significant differences in the upper bound

error between all scanners, Omnicam, 3Shape and Aadva showed clinically acceptable variations (consistently <0.3 mm) when compared to each other. Whilst TDS precision was good (Fig. 2B), there was a systematic discrepancy between its scans and those produced by Omnicam, 3Shape and Aadva. One may speculatively assume that these latter three scanners produced the truest scans. Planmeca and DWIO produced clinically intolerable disagreements with all other scanners (consistently >0.3 mm) and up to 1.16 mm in the case of DWIO compared to TDS; casting doubt on the trueness of these two scanners (Table 2).

These findings may indicate that there is merit in evaluating the maximum deviation within scan data as an adjunct to global mean distance measurements, to provide a more clinically applicable assessment. Further, as seen in the results from the Aadva, immoderate use of processing algorithms may 'game the system' and produce erroneous conclusions. This highlights the need for further investigation into edge sharpness, acuity, and clinical applicability of scanners in relation to their reported precision and resolution. Notably, IOSs are rarely capable of producing the detail of a light-bodied silicone wash, such as the bur marks typically seen in a dental crown model. Accurate mesh vertices would be required every 10–20 μm for this, whilst typical scans currently show triangles with edge lengths often exceeding 100 μm. Further work is required to investigate the *resolution* of IOSs, and indeed, whether there is any clinical detriment in this mesh simplification. It is quite possible that there is no clinical disadvantage in working with simplified data, in which case analogue dentists could consider abandoning the use of light-bodied washes, saving cost and time.

The apparent high precision of the Aadva scanner introduces the factor of the underlying 'black-box' algorithms used to collect, align, and surface scan data. These proprietary algorithms are rarely discussed, validated or developed within the dental field. As such, processing speed may be prioritized over edge definition, or reduced file size over global trueness. Such factors would not be identifiable in a precision experiment such as this but could potentially have great impact on scanner trueness and clinical application. Further investigations are required to directly assess the factors of mesh simplification and edge definition.

Full arch scanning has been shown to be less accurate than conventional impressions [4]. This is likely to be related to the problem of error accumulation and propagation whilst stitching multiple smaller scans together. Modern algorithms use loop-closure (a process where start and end points of a circular scanning path are stitched together to minimise this accumulated error). This process is simpler in the upper arch, where the palate is also scanned. It would be interesting to repeat this experiment using a lower arch form, which does not lend itself as readily to loop closure and might be expected to show poorer precision.

5. Conclusion

Both the traditional standard trimmed signed mean deviation method and the upper-bound method revealed a significant difference between the precision of some of the six intraoral scanners investigated.

The greatest global mean errors were produced by Planmeca and DWIO, but these fell just below the clinically relevant threshold of 0.3 mm in optimal measurement conditions. The upper-bound deviations of both scanners produced clinically relevant errors greater than 0.3 mm. Trios, Aadva, Omnicam and TDS all produced clinically acceptable scans according to both metrics. The investigators suggest that future studies should report both mean distance measurements and upper-bound deviation to ensure inter-study comparability and promote clinically relevant investigations.

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