JO JOURNAL OF OSSEOINTEGRATION periodontics and prosthodontics

The effect of operator scanning speed on the trueness and precision of full-arch digital impressions captured *in vitro* using an intraoral scanner

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TO CITE THIS ARTICLE
Al-Ibrahim IK, Keeling AJ, Osnes CA. The effect of operator scanning speed on the trueness and precision of full-arch digital impressions captured *in vitro* using an intraoral scanner. J Osseointegr 2021;13(4):S265-S270.

DOI 10.23805/JO.2021.13.S04.2

KEYWORDS Intraoral scanner; Trueness; Precision; Digital; Impression.

ABSTRACT

Aim This *in vitro* study aimed to assess whether different scanning speeds affected the trueness and precision of a full-arch digital impression captured using an intraoral scanner.
Materials and methods A fully dentate unprepared mandibular model (Dental Model ANA-4, Frasaco GmbH, Tettnang, Germany) was scanned using the intraoral scanner CEREC Omnicam (Dentsply-Sirona, PA, United States, Software CEREC SW 5.0). The same operator scanned the full-arch model ten times each at a slow, normal, and fast speed. Thus, the number of total scans was 30 scans. The same model was scanned with two high-resolution reference scanners to compare the trueness of each group. Linear distances between three identical key points on each scan were used as the metric throughout. Bartlett's test for Homogeneity of Multi-variances was used to assess the precision, and one-way ANOVA was used to compare the trueness across the three groups.
Results The precision did not vary significantly across any of the scanning speeds, for any of the linear distances measured ($p>0.05$ in all cases). A significant difference was found in the trueness between Standard and Slow scanning speeds for one of the three measured distances ($p=0.041$). The trueness of the other two measured distances did not differ significantly with scanning speed. The trueness of the inter-molar distance showed errors of 0.5mm or more in all cases.
Conclusions The precision of full-arch digital impressions taken using an intraoral scanner did not differ significantly when captured using different scanning speeds. The trueness of full-arch digital impressions differed significantly between Standard and Slow scanning speeds in one out of three linear measurement groups.

INTRODUCTION

The precise reproduction of a patient's dentition is an essential prerequisite for successful indirect restorations and a requirement to enable correct articulation (1-3). An inaccurate impression may result in an ill-fitting restoration, which in turn could result in failure, harm to the periodontal tissues, and affect the health of the patient's teeth (1).
Taking impressions using polyether and polyvinyl siloxane materials is done regularly in general dental practices (4). Conventional impressions have the advantage of dimensional accuracy, ease of handling, and familiarity (5). However, they have some disadvantages, such as technique sensitivity, the potential for distortion (if withdrawn too early, for example), and a potential lack of dimensional stability over time (3). Patient discomfort such as gagging, pain and uncomfortable taste are additional issues associated with traditional impression-taking (3). Direct data capture may have the potential to eliminate some of these factors (3). Using digital impressions instead of traditional methods offers possible advantages for dentists and patients, including easy scan repeatability, direct model visualisation, and the possibility of the chairside manufacturing of computer-aided design and computer-aided manufacturing (CAD/CAM) restorations (2, 6). Furthermore, digital impressions may offer enhanced patient acceptance, reduced time-related distortion of impressions (in transit to the lab etc), and possible cost and time efficiencies (7).
Much research has been done to determine IOS trueness and precision (2, 6, 8-12). The processing and investigative methods used on the data obtained for comparing

scans differ within the literature and there is no single defined clinically applicable measure for comparing 3D data in the dental field (13). A common way to measure the trueness of an IOS is to compare scans with a reference scan obtained using an ISO certified, industry standard scanner (14). Once these models are aligned, reverse-engineering programs can be used to produce colourimetric maps to show the distances and differences between the IOS surface and the reference model (14). Precision can then be measured by comparing variation between repeated scans (14).

Manufacturers often use the ability to quickly record an entire dental arch as a rationale for promoting the use of intraoral scanners. Unfortunately, there is limited literature available investigating the relationship between scanning speed and full-arch accuracy. Whether the speed with which the operator moves the intraoral scanning wand across the arch affects the quality of a scan is, therefore, a topic requiring further investigation. Recent studies on digital impression accuracy indicate that scientific evidence in this field is still needed (2). Therefore, this *in vitro* study aimed to assess whether different scanning speeds affect the trueness and the precision of the full-arch digital impression.

The null hypothesis for this experiment was that no difference would be found in the trueness and precision of the full-arch digital impression regardless of the speed with which the operator moved the scanner across the dental arch.

MATERIALS AND METHODS

A fully dentate unprepared mandibular model (Dental Model ANA-4, Frasaco GmbH, Tettnang, Germany) was used in this study. This model was scanned using the intraoral scanner CEREC Omnicam (Dentsply-Sirona, PA, United States, Software CEREC SW 5.0). The model was scanned in the phantom head ten times at slow speed, ten times at normal speed, and ten times at fast speed by the same experienced operator and the scans were exported as standard tessellation language (STL) files. The scanning speed was divided into three groups: a slow speed (S), which took 4 minutes, an average speed (A), which took 2.5 minutes, and a fast (F) speed, which took 1.5 minutes. The scanning method was performed according to the manufacturer's instructions (15). The same model was then scanned using two high-resolution laboratory scanners: the inEos X5 (Dentsply-Sirona, PA, United States), which the manufacturer claims to have an accuracy of 2.1 µm, and the 3Shape D2000 (3Shape, Copenhagen, Denmark), which the manufacturer has stated has a 4 µm accuracy. These two scanners were used to get an indication of the trueness of each sample scan produced by the CEREC Omnicam. The average measurement values produced by the two laboratory scanners was used as the "gold standard" measure for this study.

Prior to analysis, each STL file was subsampled uniformly to create point clouds with a sample every 0.025 mm, using custom software. All subsampled points were true locations on the triangle faces of the mesh. All scans from each group were then aligned to the first scan (A1) of group A (Average speed), which was used as a reference scan. Three key points were manually identified on scan A1 as follows.

- The cusp tip of the mesiobuccal cusp on the lower right second molar (R7).
- The cusp tip of the mesiobuccal cusp on the lower left second molar (L7).
- The mesial incisal angle of the lower right central incisor (R1) (Fig. 1).

On all remaining scans, identical anatomical key points were identified, using an automated process that precisely mapped the topologically identical key point from A1 onto the recipient scan. This process has previously been reported (16) and validated (17), but warrants a detailed description: a cropped, local region (radius 10 mm) of the mesh was tightly aligned to the donor scan (A1), leveraging the fact that the shape of this small region produced a closer match to the equivalent region on the donor scan, as opposed to two globally aligned scans over the full arch. Once aligned, the closest point on the surface of the cropped test scan to the key point on the donor scan was

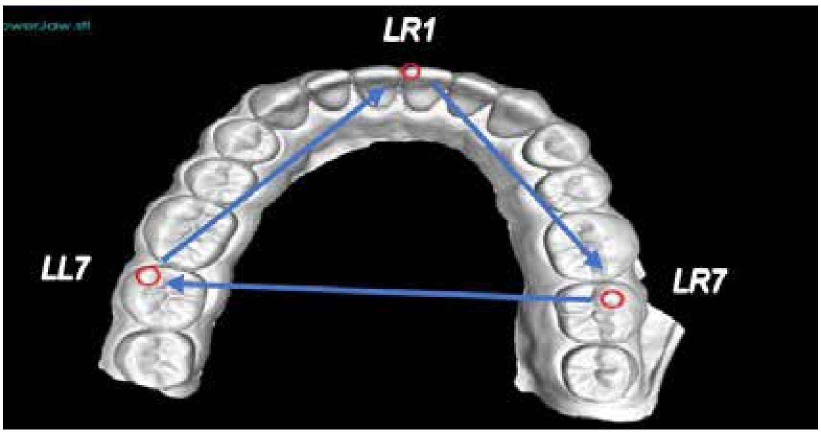

FIG. 1 Illustration of anatomical key points identified on each scan, enabling direct comparisons of variation in distances across the arch.

	Average error L7 to R1 (mm)	Average error R1 to R7 (mm)	Average inter-molar error L7 to R7 (mm)
Standard	-0.014 (±0.025)	0.165 (±0.024)	0.518 (±0.103)
Fast	0.021 (±0.031)	0.154 (±0.027)	0.619 (±0.071)
Slow	0.025 (±0.036)	0.134 (±0.052)	0.588 (±0.146)

TABLE 1 "Error" is the deviation of the average of each scan speed group (n=10) compared to the average linear measurement produced by InEos and D2000 laboratory scanners.

identified. The small alignment motion that the test scan had undergone was then 'unwound', bringing it, and the newly identified key point, back into the original position. This process was repeated separately for all three key points on each scan. Custom software developed by the Leeds School of Dentistry using the Visualization Toolkit (18), was used to perform these tasks. Linear distance measurements were recorded between the three key points in each scan. Thus, L7 to R1, R1 to R7 and finally, R7 to L7 (inter-molar distance). Key points were similarly identified on the two reference scans, in Eos and D2000, using A1 as the donor scan, and the average distances produced by the two scans was used as the "gold standard" value.
Data were evaluated using the SPSS (IBM Corp, version 26.0, Armonk, USA) (19) and initially tested for normality using the Shapiro-Wilk test. Bartlett's test for Homogeneity of Multi-variances was used to assess whether the variance (precision) differed between the three different scan speeds. Using one-way analysis of variance (ANOVA) with Bonferroni Correction, the mean errors were compared across the three scan speeds (trueness). The level of significance was set to $\alpha = 0.05$ throughout.

RESULTS

Shapiro-Wilk analysis showed all data were normally distributed ($p>0.05$ in all cases). The two model scans showed small deviations in the distances between key points; 0.015 mm (R7-R1), 0.013 mm (R1-L7), 0.045 mm (L7-R7). The means of these key point separations were calculated and used as the gold standard for all subsequent Omnicam comparisons; 41.998 mm (R7-R1), 40.613 mm (R1-L7), 49.087 mm (L7-R7).

Precision

Bartletts Test for homogeneity of variance showed no significant differences across the three scan speeds, for any of the three segments ($p>0.05$ in all cases).

Trueness

The mean errors (+/- sd) for all three scan speeds, for all three segments are shown in Table 1.
For L7-R1, ANOVA showed a significant difference in trueness across the three scan speeds ($p=0.026$). Post-hoc pairwise analysis with Bonferroni correction revealed a significant difference in trueness between Standard and Slow scanning ($p=0.041$) (Fig. 2).

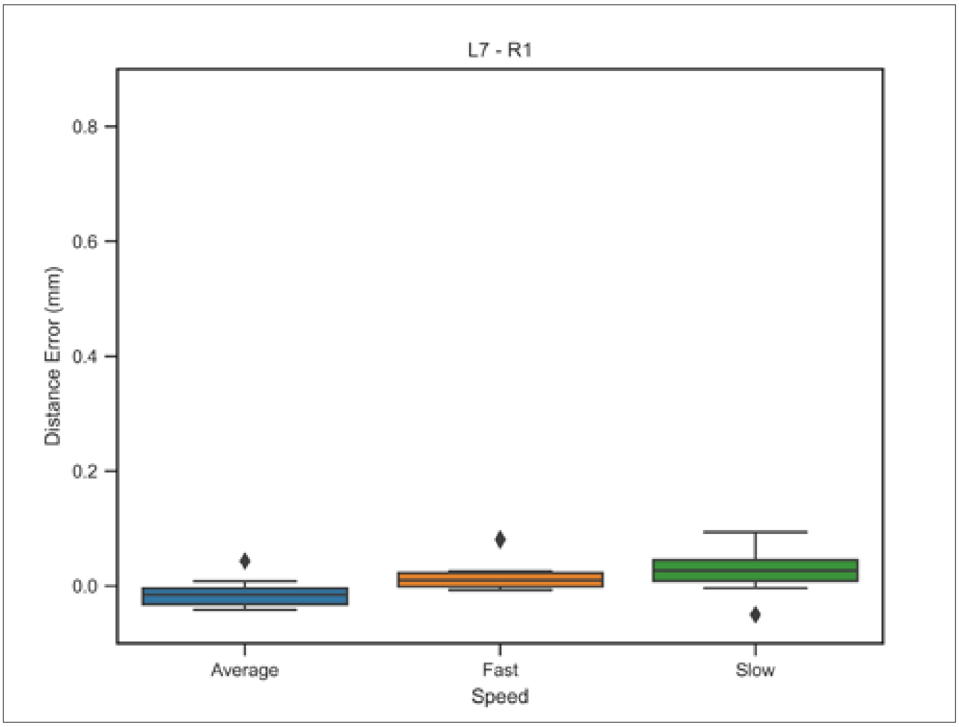

FIG. 2 Distance errors between key points L7-R1. "Distance error" is the deviation of the average of each scan speed group (n=10) compared to the average linear measurement produced by the InEos and D2000 laboratory scanners.
The line indicates median value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond.

For R1-R7, ANOVA showed no significant differences in trueness across the three scan speeds (p=0.207) (Fig. 3). For L7-R7, ANOVA showed no significant differences in trueness across the three scan speeds (p=0.158) (Fig. 4).

DISCUSSION

Identifying the level of error introduced at the various stages of the digital workflow would be of value. For this reason, this *in vitro* study aimed to assess whether different scanning speeds affect the trueness and precision of the full-arch digital impression. The null hypothesis of the experiment was that no difference would be found in the trueness and precision of the full-arch digital impression regardless of the speed with which the operator moved the scanner across the dental arch. We compared the trueness and precision of average, fast, and slow scan speeds, measuring

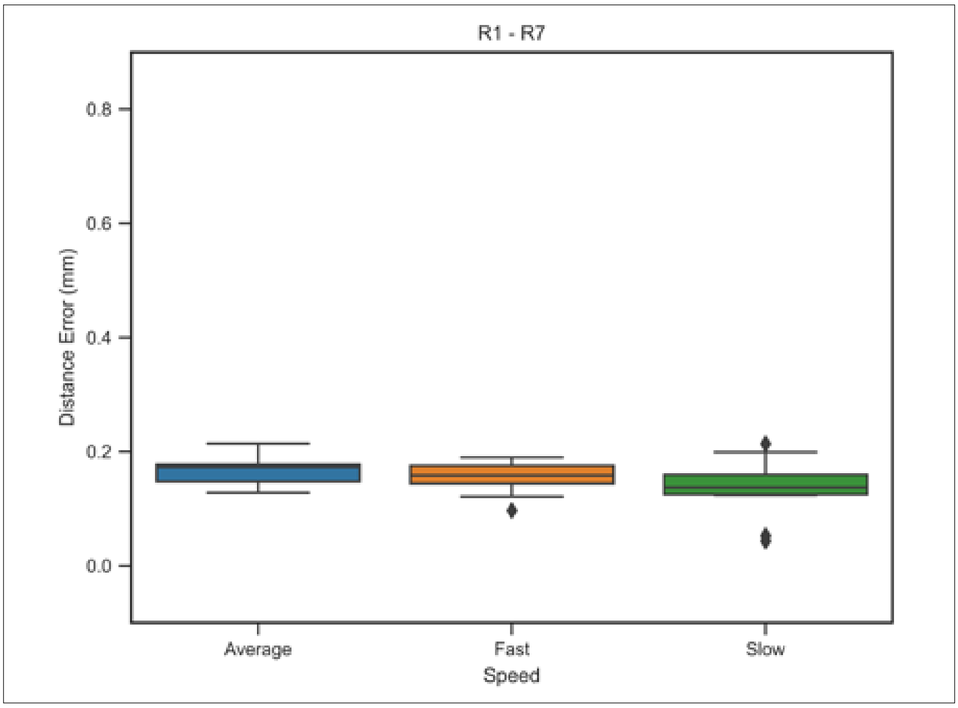

FIG. 3 Distance errors between key points R1-R7. "Distance error" is the deviation of the average of each scan speed group (n=10) compared to the average linear measurement produced by the InEos and D2000 laboratory scanners.
The line indicates median value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond.

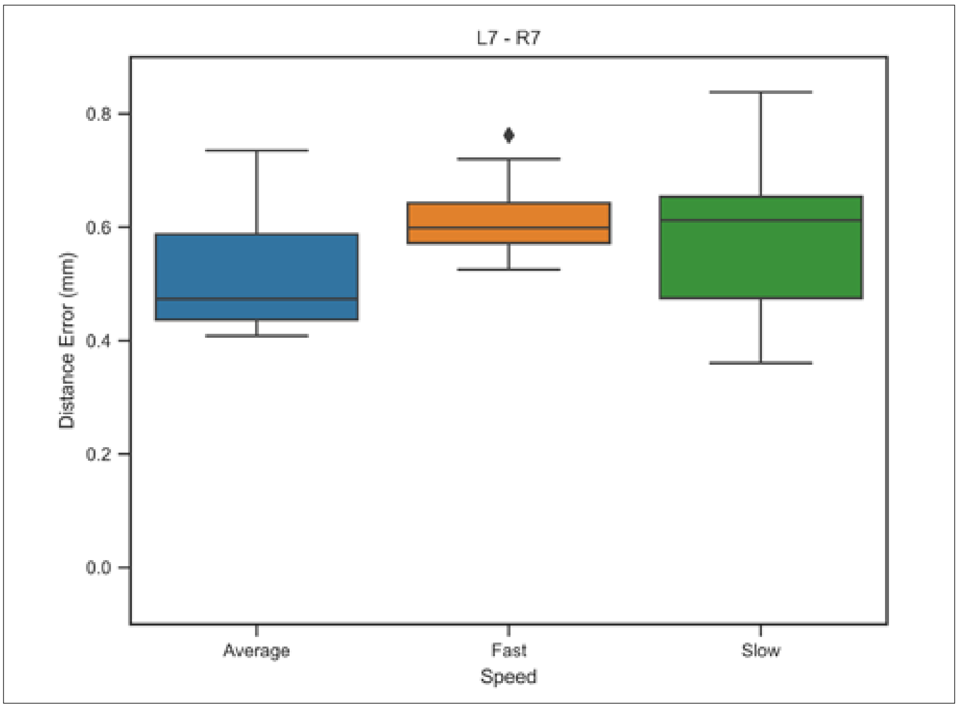

FIG. 4 Distance errors between key points L7-R7. "Distance error" is the deviation of the average of each scan speed group (n=10) compared to the average linear measurement produced by the InEos and D2000 laboratory scanners.
The line indicates median value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond.

antero-posterior distances (L7-R1 and R1-R7) and the intermolar width (L7-R7) to get an insight into the location of any distortion.

Precision was not statistically significantly different among the three scan speed groups for the three tested distance segments. Hence, the null hypothesis is accepted: the scan speeds did not alter the precision for inter-molar and antero-posterior distances. Furthermore, scanning speed did not cause significant differences in trueness for the distances between R1-R7 and R7-L7. However, trueness was significantly affected by scan speed for L7-R1, with Standard and Slow speeds differing significantly ($p=0.042$). Therefore, the null hypothesis that the scan speeds did not affect the trueness is rejected.

When considering our results in a clinical context, it should be noted that the L7-R1 distance errors for the Standard and Slow groups (the only instances to differ significantly in trueness) were generally a factor of 10 smaller than the other two segments (-0.014 mm and 0.025 mm respectively). The scale of these trueness errors might therefore be considered clinically insignificant. Note also that standard speeds for this group tended to underestimate the distance (mean error -0.014 mm), while slow scan speeds tended to overestimate (0.025 mm). This might reflect 'black box' tuning by the manufacturer, in relation to the parameters used for local point cloud alignment. Within the tolerances of the scanning accuracy, the scanner is likely to have been tuned to be, on average, locally optimal. Thus any systematic errors caused by variations in wand speed will be evenly distributed about this mean.

When considering the remaining two measurement distances (R1-R7 and R7-L7, which were derived from the latter half of the scan motion and so subject to larger cumulative errors), no significant differences in trueness were found. However, more error in trueness was introduced, resulting in the clinically unacceptable intermolar width errors seen in all scan groups. This is worthy of note, as these findings reinforce the general conclusion within the field, that IOS may be appropriate for quadrant dentistry, while likely to be clinically inappropriate for full-arch appliances and larger work.

Our findings show that once the wand has travelled a greater distance (more than a quadrant), any variations in trueness which may be caused by wand speed are dwarfed by the larger cumulative errors accumulated as the scanner attempts to align multiple sequential scans. These errors are of a clinically significant magnitude (0.134-0.165 mm within the second quadrant (R1-R7), and 0.518-0.619 mm across the molars (R7-L7). Therefore the Omnicam cannot be recommended for use in full arch cases, regardless of careful operator technique.

Handling and analysing 3D data in a clinically relevant manner is a recognised challenge (6). There is a lack of agreement within the dental field on clinically relevant metrics to assess and compare 3D data (6). Most methods commonly used within the digital dentistry field rely on alignment, or superimposition, of multiple scans prior to analysis (20). Three-dimensional alignment is not trivial and is vulnerable to error (20). Unfortunately, the level of success, or failure, of 3D alignment is frequently hidden from the operator, particularly if the analysis is undertaken in user interface-based software solutions (20). Erroneous alignments may thus not be immediately apparent to the operator, which may lead to erroneous conclusion (20). This issue of relying on global alignment has been raised in a handful of previous papers (6, 8, 20, 21). The key point method, which has been used in this study, precisely identifies the same topological point on each scan, allowing distances to be measured directly, without being dependent on correct global alignment. A method relying only on whole arch alignments, and reporting the resulting mean deviation measurements, would also produce less conceptually accessible results and potentially lead to misleading conclusions (6, 16). Thus, the key point method has two main advantages:

1) No full arch alignment is relied upon for analysis, with all measurements being taken from within one scan rather than across potentially poorly aligned scans.
2) The metric distance measurements collected present a more clinically accessible insight into arch error than an averaged surface comparison, which would dramatically under-estimate errors, and produce conceptually diffuse results (6).

A 2018 review found that the accuracy of digital impressions was considered clinically adequate for the manufacture of crowns and short FPDs (22). However, the conventional technique was considered more appropriate than digital impressions for large and full-arch FPDs, as error accumulates over larger scan spans (22). The main two findings of the current study were, firstly, that the trueness and precision of full-arch scans were not clinically affected by the speed of the scan, and, secondly, that there was a lack of trueness, regardless of which scan speed was used, over larger cross arch scans. Intermolar (R7-L7) deviations of 0.4-0.6mm were measured with all scan speeds, and these errors would be considered highly clinically relevant. For example, errors below a limit of 0.2 mm for full dentures have previously been recorded as clinically acceptable (23). More recently, differences in maxillary and mandibular dentures in the posterior region have traditionally approached 0.25 mm when flasked (24). Hence, 0.3 mm errors may be considered clinically significant and inferior to current best practice. All scan speeds created inter-molar errors that would be considered clinically relevant at 0.5

mm or more. These errors could affect the success of an appliance; local deviations of more than 0.1 mm can lead to incorrect fittings, causing problems with extensive prosthetic restorations (9, 25, 26).

The current study investigated the impact of IOS scanning speed on scan accuracy. The study was undertaken using the CEREC Omnicam intraoral scanner. While no longer the flagship scanner of Dentsply Sirona, it is still used in clinics worldwide. Whether other IOSs are affected differently by operator scanning speed remains unanswered. Whether edentulous areas or teeth preparations, as opposed to the unprepared, fully dentate model used in this experiment, would affect the accuracy of the completed scan would benefit from further research. Likewise, whether the results would differ *in vivo* due to variables such as humidity, oral structures, patients' saliva and patient movement should be assumed but warrant further investigation.

CONCLUSIONS

Under the limitations of the current study, it can be concluded that there was no statistically significant difference in the precision of full-arch scans acquired using a CEREC Omnicam intraoral scanner at different operator scanning speeds. However, there was a statistically significant difference in the trueness of L7-R1 distance when scanning at Standard and Slow speeds. Furthermore, the scanner did show a lack of trueness, irrespective of the scan speed. All three scanning speeds produced inter-molar trueness errors more significant than 0.5 mm, which would be considered clinically significant. Therefore full-arch dentistry cannot be recommended when using this device.

Conflict of interest

AJK is a founder, director, shareholder and consultant for Mimetrik Solutions and a consultant for GC Corporation.

CAO is a founder, shareholder and employed by Mimetrik Solutions.

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