Precision of maxillo-mandibular registration with intraoral scanners in vitro

ORIGINAL ARTICLE

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ABSTRACT

Purpose: To compare the precision of maxillo-mandibular registration and resulting full arch occlusion produced by three intraoral scanners in vitro.

Methods: Six dental models (groups A–F) were scanned five times with intraoral scanners (CEREC, TRIOS, PLANMECA), producing both full arch and two buccal maxillo-mandibular scans. Total surface area of contact points (defined as regions within 0.1 mm and all mesh penetrations) was measured, and the distances between four pairs of key points were compared, each two in the posterior and anterior.

Results: Total surface area of contact points varied significantly among scanners across all groups. CEREC produced the smallest contact surface areas (5.7–25.3 mm^2), while PLANMECA tended to produce the largest areas in each group (22.2–60.2 mm^2). Precision of scanners, as measured by the 95% CI range, varied from 0.1–0.9 mm for posterior key points. For anterior key points the 95% CI range was smaller, particularly when multiple posterior teeth were still present (0.04–0.42 mm). With progressive loss of posterior units (groups D–F), differences in the anterior occlusion among scanners became significant in five out of six groups (D–F left canines and D, F right canines, $p<0.05$).

Conclusions: Maxillo-mandibular registrations from three intraoral scanners created significantly different surface areas of occlusal contact. Posterior occlusions revealed lower precision for all scanners than anterior. CEREC tended towards incorrect posterior open bites, whilst TRIOS was most consistent in reproducing occluding units.

1. Introduction

The ability to record and reproduce the maximal intercuspation position (ICP) is pivotal to prosthetic workflows. As intraoral scanning (IOS) becomes increasingly popular in dental medicine, interest in its ability to record ICP using an automatic bite scan function is growing [1–5]. Early studies with fully dentate situations focused on sectional digital impressions in combination with buccal maxillo-mandibular scans in the exact region of interest [4,5]. More recently, the use of IOS has been investigated in full arch situations [6–10], and a decreased trueness and precision of the obtained scans has been observed when compared to conventional impressions [7,8,10,11]. This imprecision was related to cumulative errors in the stitching process with overlapping pictures in a curved arch [12], and potentially affected the quality of full arch IOS maxillo-mandibular registration as well. From a clinical point of view, it is still not clear how many antagonistic contacts are necessary using the automatic bite function of the IOS software to achieve a reliable and reproducible result to transfer the patient's ICP. Furthermore, the clinical borderline scenario of commercially available IOS devices for full-arch scans and maxillo-mandibular registration is poorly understood.

Therefore, the aim of this in vitro investigation was to compare the ICP occlusions produced by three contemporary IOS systems using six clinical models with consecutively reduced numbers of antagonists in full arch situations. These data are required to identify the limitations of IOS technology when implemented into routine clinical practice for automated maxillo-mandibular registration. ICP occlusion was defined using two separate metrics: (i) presence of, and total surface area of, tooth contacts; and (ii) separation distance between four pairs of key points located around the arch. The null hypotheses (H_0) were that there is no difference in the mean surface area of contact points among the three included IOS systems, and no difference in the inter-arch separation measured at four pairs of key points around the arch.

2. Materials and methods

2.1. Study set-up

A fully dentate maxillary and mandibular reference model (Dental Model ANA-4, Frasaco GmbH, Tettnang, Germany) was used to create six different study model pairings, sequentially simulating clinical scenarios according to defined antagonistic contact schemes (groups A–F). Model situation “A” was fully dentate (Eichner Class A1) and the additional five pairings represented a consecutive reduction in the number of teeth with edentulous spaces and free-end situations (Eichner Class A2 to B4)[13]. From the specific model situations, silicone forms were produced (Picodent Twinsil 22, Picodent, Wipperfürth, Germany) and used to fabricate stable acrylic resin models. The teeth were poured with a tooth color cold-curing resin (A 3.5 Enamel Plus Temp Lab, Micerium, Avegno, Italy), while the gingiva and the bases were produced in pink cold-curing polymethylmethacrylate material (Candulor Aestehtic Blue in Color 34, Candulor AG, Glattpark, Switzerland). All models were mounted with a class III dental stone (Artifix, Amann Girrbach GmbH, Pforzheim, Germany) on a semi-adjustable arcon-articulator (SAM 2P, SAM Präzisionstechnik GmbH, Gauting-Munich, Germany), and occlusal planes were adjusted with a bur (football 022, ISO ∅ 1/10 mm, 40 µm, Intensiv SA, Montagnola, Switzerland) to establish occlusal contacts with 8 µm shimstock foil for each antagonistic pair including the anterior dentition.

Three different IOS systems (CEREC Omnicam, Sirona-Dentsply, Bensheim, Germany, Software Ortho SW 1.2; 3Shape TRIOS, Copenhagen, Denmark, Software 1.4.7.3; PLANMECA Emerald, Roselle, IL, USA, Software Romexis 5.0.0.R.) were involved in the study and used by three calibrated specialists in reconstructive dentistry within three weeks. Models from all six groups were digitized initially by scanning single maxillary and mandibular full arches and performing maxillo-mandibular registrations from both left and right buccal sites between canine and last molar. The full scanning process of maxilla (n=6), mandible (n=6) and two maxillo-mandibular registrations (n=12) in static occlusion was repeated five times for each clinical scenario (total maxilla/mandible n=30, bite n=60).

2.2. Scan strategy

Full arch scans were obtained including edentulous regions, except the palatal area in the maxilla. The scan strategy was based on the manual step-by-step instructions and recommendations provided by each IOS manufacturer (**Fig. 1**). After scanning, standard tessellation language (STL) files were gathered and used for comparison of the automatic maxillo-mandibular registration function of the IOS software as detailed below.

2.3. Maxillo-mandibular registration analysis

An assessment of the surface area in contact was performed for each pair of digital models (upper and lower). To avoid uneven sampling across variable sized triangles in the meshes, each STL file was first subsampled uniformly to create point clouds with a sample every 25 µm. These new points were all valid positions on the face of a mesh triangle and each point represented a surface area of 0.000625 mm^2. For each occlusal scan-pair, the number of points in the upper arch which were within 100 µm of the closest point in the lower arch, and all negative penetrating points, were recorded. This method yielded a measure of the total surface area of contact points. In addition, each color mapped upper scan was inspected for the presence of virtual occlusal contacts on each tooth. Any false negatives (no recorded virtual contact despite a known shimstock hold) were tallied to search for patterns of error.

An additional quantification of the variation in maxillo-mandibular registration was performed aligning all upper models from the three scanners into the same coordinate system of the first scan (CEREC A1), which served as reference. The transformation matrix for each motion was applied to the corresponding lower model, which had the effect of bringing each lower model (maxillo-mandibular registration) into the common coordinate system without altering the individual inter-arch relationship. Four key points were identified on the first scan-pair (CEREC A1), located in the upper jaw on the area of the canine and second molar on the left and right site indicated as UL7, UR7, UL3, and UR3. Corresponding points located vertically below the upper points were identified in the lower arches. Identical anatomical key points were identified on all scans and distance measurements between each pair were recorded to allow for direct comparison. To ensure consistent measurements on all the remaining scan-pairs, each test arch in turn was cropped to produce 10 mm regions around the region of each key point and this local 'patch' was tightly aligned to the CEREC A1 reference arch (**Fig. 2**). The precise location of the measurement point was then determined as the closest point on the test patch to the original key point. The small transformation that the test patch had undergone was then reversed, carrying the key point with it. This method accurately identified the same topological point on each test-pair, allowing direct comparison of the distances. This was necessary because the errors in full arch intraoral scans were too large to rely upon a full arch alignment of one scan to another. Cross-arch width variations of several hundred micrometers can occur and this method ensured that measurements were being taken from anatomically identical points on each tooth, thereby allowing a valid comparison across scanners (**Fig. 2**).

In all cases, custom software written by Leeds School of Dentistry, using the Visualization Toolkit, was used to perform these tasks [14]. Linear measurements between each pair of points were recorded. The variation in the linear distance between point-pairs was recorded wherever possible (the second molar key points disappeared in groups D–F).

2.4. Statistical analysis

For each group and each IOS, the mean surface area in contact was measured. The normality and homoscedasticity for each measurement were assessed by Kolmogorov-Smirnov test and Levene's test, respectively. The differences between groups were assessed for significance using one-way ANOVA. Differences in the distances between the pairs of key points for CEREC, TRIOS, PLANMECA and groups A–F were also analyzed using one-way ANOVA. If multiple comparison was performed using t-test, p-values were adjusted with Bonferroni correction. The level of significance was set to $\alpha = 0.05$.

3. Results

After viewing the scans, one set (CEREC D4) had to be excluded due to a gross intra-arch scanning error (only three lower incisors were present on the digital model). A further set (CEREC F4) showed a gross error in surface orientation over an edentulous region causing a large false result when assessing contact point area and this scan was excluded from the surface area analysis.

All measurements were checked for normality and homoscedasticity, and the assumptions were not violated. Therefore, ANOVA and t-test with Bonferroni correction were used to assess the difference among groups where appropriate.

3.1. Contact point surface area

Contact point surface areas differed significantly across all three scanners for all groups ranging from 5.7 mm^2 (CEREC, group E) to 66.7 mm^2 (TRIOS, group D), and were not continuously reduced in groups A to F. In all scenarios except for group D, the recording with PLANMECA resulted in the largest mean occlusal surface area (**Tab. 1**). In group D with antagonistic edentulous spaces and a unilateral free-end saddle in the lower jaw (Eichner Class B1), the TRIOS revealed the largest surface area. For the test groups with posterior teeth (A–D), CEREC produced the least surface area in contact. For groups E and F with anterior contact (Eichner Class B2 and B4), the variation in contact surface area among scanners was reduced, but PLANMECA still tended to produce a greater contact surface area (**Tab. 1**).

3.2. Visual inspection of occluding units

The frequency and pattern of detected occluding units for each scanner is shown in Figure 3. CEREC had a tendency to incorrect posterior open bites and failed to detect any occluding units on the second molars for test groups A and B (Eichner Class A1 and A2). TRIOS correctly identified the most occluding units, while PLANMECA showed more errors in anterior occluding units. All three IOSs correctly identified the occluding canines in Group F at every attempt (**Fig. 3**).

3.3. Key point analysis

The mean inter-occlusal distance between each pair of key points showed large variations within repeated scans from each IOS (**Tab. 2**). The poorest precision, as indicated by a large 95% CI, was seen in UL7-LL7 group C PLANMECA (mean: 0.55 mm; 0.1–1.0 mm 95% CI). Higher precision, as noted by a smaller 95% CI, was seen for anterior key points for all scanners. The smallest CI range was 0.04 mm and was recorded in several anterior groups, for example UR3-LR3 group A CEREC (mean: 2.17 mm; 2.15–2.19 mm 95% CI) and UR3-LR3 group D TRIOS (mean: 1.83 mm; 1.81–1.85 mm 95% CI). No obvious trend in the precision of maxillo-mandibular registration was observed with the progressive loss of teeth over groups A–F for CEREC and TRIOS. For PLANMECA, the 95% CI of the molar key point measurements tended to increase as posterior teeth were removed, indicating a decrease in precision.

Comparing mean posterior key point separations across IOSs, typical discrepancies of 0.2 mm were observed (for example UR7-LR7 in group A: CEREC 1.03 mm, TRIOS 0.94 mm, PLANMECA 0.80 mm; total range 0.23 mm). The reported differences were statistically significant in three of the seven cases (UR7-LR7 groups A, B and UL7-LL7 group B). In the presence of multiple posterior units (groups A-C), the mean anterior key point separation distances showed no significant differences between scanners, with values typically less than 0.1 mm (**Tab. 2**). With further loss of molar units (groups D-F), the reported mean anterior key point separation distances differed significantly between the three IOSs in every situation (except UR3-LR3 group E), with a maximum discrepancy of 0.31 mm (UR3-LR3 group F CEREC versus PLANMECA). In groups D-F, CEREC and TRIOS agreed closely with regard to mean anterior key point separation distances, whilst PLANMECA appeared to be the outlier.

4. Discussion

The aim of this in vitro study was to compare the precision of automatic maxillo-mandibular registrations in consecutively reduced dentitions to identify the clinical threshold for a reliable automatic maxillo-mandibular registration. Large variations were observed in the occlusal contact surfaces among the three tested intraoral scanners.

The results from the current in vitro study must be interpreted with caution, since in vivo scanning is associated with confounders which may adversely affect the precision such as moisture, condensation, and encumbered wand positioning [10,15]. Due to the differences associated with the six bite situations, absolute comparisons across groups A–F in terms of trueness were not feasible, but the precision (variation about the mean) and the variation among scanners were evaluated across each group. For precision testing of STL files, a visual analysis of occluding units is relatively crude and will not detect overclosures. Open bites are, however, detectable, such as the systematic error in CEREC scans with incorrect posterior open bites within the highly dentate groups (A–C).

The current study demonstrated significant variations in total surface areas of contact points among the investigated IOS and also among the groups A-F. Instead of a continuous reduction from group A to group F according to their reduction in occluding units, data revealed only a trend to greater surface areas of contact points in group A-D compared to E and F. This observation is in line with the variation in visual occluding units among the three IOS. TRIOS and PLANMECA tended to show contact points distributed around the arch, in line with the established occlusion. CEREC produced posterior open bites, which would lead to high restorations and may explain the need for a manually tuned 'occlusal offset' established in the CEREC milling software. PLANMECA revealed some intra-arch variability (stochastic error) with anterior regions in open bite, others in overclosure, which makes it difficult to predict the direction of the occlusal error from this scanner and to ascertain a simple corrective offset value. TRIOS produced surface areas of contact points that lay in-between the other scanners and might be considered the most likely to be correct. In addition to the risk of incorrect restorations with premature contacts or missing occlusal contacts, it must be noted overclosure is a phenomenon restricted to IOS, which can not be produced with conventional model mounting.

The source of the occlusal discrepancies amongst IOS, and the reasons of the lack of precision within some IOS, is unclear. One reason might be the quality of the full arch scan using different scan strategies since cross-arch distortions are known to occur [11], and this could have a knock-on effect on any attempt to create an occlusion. Indeed, the trend towards using bilateral buccal maxillo-mandibular scans as opposed to a single bite scan in the region near an abutment tooth may be counterproductive. If arch distortions have occurred, the occlusal algorithm must find a best fit from two maxillo-mandibular scans, where such a fit does not exist. Occlusal errors will be distributed evenly around the arch to produce the best average occlusion, but result also in partially inaccuracy everywhere.

A single bite scan will suffer less from cross arch scanning errors and should perhaps still be recommended if all dental work is restricted to one quadrant.

The key point analysis allowed for comparisons of physical displacements across the three IOS systems, and for displacement analysis across repeated scans of the same models. In the current study, differences were observed in the inter-arch separation measured at four pairs of key points around the arch, and the clinical application of IOSs for full arch occlusal cases with molar units cannot be recommended based on the current work. PLANMECA showed larger 95% CIs compared to TRIOS and CEREC, indicating poorer precision. The largest 95% CIs were seen in molar occlusions, the greatest being UL7-LL7 PLANMECA group C (mean: 0.55 mm; 0.1–1.0 mm 95% CI), and the magnitude of this interval seems clinically unacceptable. CEREC and TRIOS showed better precision with the widest 95% CI for CEREC observed in UR7-LR7 group C (mean: 0.86 mm; 0.67–1.03 mm 95% CI) and for TRIOS in UR7-LR7 group B (mean: 0.65 mm; 0.49–0.81 mm 95% CI). The variations found were of a clinically significant magnitude and it can be assumed that the molar occlusion produced by the three IOS would be detectably different on any restoration made from such scans. However, statistically significant differences in mean molar separation distance across the IOSs was seen in only three out of seven test groups (groups A and B UR7-LR7 and group B UL7-LL7). The lack of statistical significance in the remaining groups may be explained by the large standard deviations, particularly for PLANMECA. By contrast, the range of mean anterior key point separation distances among the IOS systems was much smaller when multiple posterior teeth were still present (groups A–C). Confidence intervals were small, indicating a high precision in recording the anterior occlusion, as long as a reasonable number of posterior units remain. It is interesting to note that the molar key point variations were of the same order of magnitude as the cross-arch errors observed in previous studies [3]. Similarly, the magnitude of the anterior key point variations agreed well with previous reports of occlusal variation close to the buccal maxillo-mandibular scan [4,5]. One might conclude there is a bias towards higher accuracy in the anterior region when recording a digital bite. This might be because the bilateral buccal maxillo-mandibular scans envelope the anterior region, creating well-defined points of reference for the occlusion. It is difficult to prevent the posterior ‘free ends’ from diverging because there is no maxillo-mandibular scan data at, or beyond, the last standing molars. With the loss of posterior units (groups D–F), differences in the anterior occlusion between IOSs became significant in five out of six cases. These differences stem from a disagreement between the PLANMECA occlusions and the other two IOSs. The true occlusal separations were not known, but one might postulate that the close agreement between CEREC and TRIOS hints at these two IOSs producing the correct anterior occlusion, whilst PLANMECA became prone to error.

5. Conclusion

Maxillo-mandibular registrations from three tested IOSs produced significantly different surface areas of occlusal contact, and the magnitude of the variation in molar separation between those IOSs was significant. CEREC tended to create incorrect posterior open bites, while TRIOS showed more uniform occlusions. Further work is required to investigate the trueness of the ICP occlusions produced by IOSs before they could be recommended for full arch digitization with confidence; but based on the present findings, TRIOS produced occlusions which were closest to the true value.

Anterior occlusions, bounded by the bilateral buccal maxillo-mandibular scans, showed higher precision for all the tested IOSs and might be more clinically reliable than posterior IOS occlusions. However, additional confounders in the clinical setting will adversely affect the occlusal recording and further in vivo work is indicated before a firm recommendation can be made.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Müller HC. Registration of occlusion by buccal scan in Cerec software version 3.80. Int J Comput Dent 2010;13:265–73.

[2] Straga RW. Comparison of occlusal contacts on mounted dental models to contacts identified on digital 3D models using a new virtual alignment method. MSc thesis, University of British Columbia, Vancouver, CA, 2009.

[3] Iwaki Y, Wakabayashi N, Igarashi Y. Dimensional accuracy of optical bite registration in single and multiple unit restorations. Oper Dent 2013;38:309–15.

[4] Ueda Y, Okada D, Ogura R, Komada W, Otake S, Ikeda M. Evaluation of occlusal relationship reproducibility with CAD / CAM techniques. Asian Pacific J Dent 2014;14:35–40.

[5] Jaschouz S, Mehl A. Reproducibility of habitual intercuspation in vivo. J Dent 2014;42:210–8.

[6] Ender A, Mehl A. Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision. J Prosthet Dent 2013;109:121–8.

[7] Ender A, Mehl A. Full arch scans : conventional versus digital impressions – an in-vitro study. Int J Comput Dent 2011;14:11–21.

[8] Ender A, Attin T, Mehl A. In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions. J Prosthet Dent 2016;115:313–20.

[9] Patzelt SBM, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 2014;18:1687–94.

[10] Flügge T V., Schlager S, Nelson K, Nahles S, Metzger MC. Precision of intraoral digital dental impressions with iTero and extraoral digitization with the iTero and a model scanner. Am J Orthod Dentofac Orthop 2013;144:471–8.

[11] Ahlholm P, Sipilä K, Vallittu P, Jakonen M, Kotiranta U. Digital versus conventional impressions in fixed prosthodontics: a review. J Prosthodont 2018;27:35–41.

[12] Sprickerhof J, Nüchter A. A heuristic loop closing technique for large-scale 6d slam. Automatika 2011;52:199–222.

[13] Eichner K. A group classification of missing teeth for prosthodontics. Dtsch Zahnarztl Z 1955;10:1831–1834.

[14] Schroeder W, Martin K, Lorensen B. The visualization toolkit (4th ed.). Kitware; 2006.

[15] Keeling A, Wu J, Ferrari M. Confounding factors affecting the marginal quality of an intra-oral scan. J Dent 2017;59:33–40.