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RESEARCH AND EDUCATION

Evaluation of repeatability of different alignment methods to obtain digital interocclusal records: An in vitro study

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ABSTRACT

Statement of problem. The alignment of the maxillary and mandibular digital scans obtained with an intraoral scanner (IOS) generates digital interocclusal records. Although the accuracy of maxillary and mandibular digital scans obtained from an IOS is widely studied, the accuracy of digital interocclusal records obtained with them is not; even less studied is the accuracy (trueness and precision) of the alignment methods that are available to obtain them.

Purpose. The purpose of this in vitro study was to assess the precision under repeatability conditions (repeatability) of the different alignment methods used to obtain digital interocclusal records.

Material and methods. Digital scans of maxillary and mandibular casts of a dentate healthy adult were acquired with an IOS. Casts were then mounted in maximum intercuspal position in a semi-adjustable mechanical articulator (1801 AR Model PSH Articulator), and left and right occlusal digital scans were acquired with the IOS. Occlusal digital scans were repeated 7 times under repeatability conditions. After obtaining each pair of occlusal digital scans, the software program of the IOS automatically aligned the maxillary and mandibular digital scans with occlusal digital scans (TRI method), resulting in 7 digital interocclusal records composed of aligned maxillary and mandibular digital scans and occlusal digital scans. All 7 sets of aligned digital scans were exported and realigned in a dental computer-aided design software program by means of global and reference alignment methods (EXO-B and EXO-R methods, respectively). To assess the repeatability, the 7 aligned digital scan sets of each group were repositioned in the common coordinate system by aligning maxillary digital scans, and repeatability was calculated in terms of the distance between the vertices of the mandibular digital scans for each of the possible nonrepeating combinations of pairs ($^{7}C_{2}$=21). The repeatability was tested by using the Kruskal-Wallis test for nonparametric distribution followed by the Mann-Whitney U test and Bonferroni correction for pairwise comparisons (α=.05).

Results. The median with interquartile range for the TRI alignment method was 47 (27) μm for the EXO-B method 41 (25) μm and 16 (5) μm for EXO-R. The Kruskal-Wallis test showed statistical difference between test groups (P<.05). The post hoc Dunn test with Bonferroni adjustment detected significant statistical differences between the EXO-R–TRI (P<.001) and EXO-R–EXO-B (P<.001) alignment methods.

Conclusions. This study found that the alignment method could influence the repeatability of digital interocclusal records. The reference best-fit alignment method (EXO-R) provided better repeatability. (J Prosthet Dent 2024;131:709-17)

Intraoral scanners (IOSs) allow both the digital scans of dental arches and digital interocclusal records to be obtained directly from a patient's mouth. The accuracy of the intraoral digital scans of dental arches has been extensively studied,[1-7] while the number of studies on the accuracy of intraoral digital interocclusal records has increased over the last few years.[8-13]

Digital interocclusal records with an IOS are usually obtained by performing 2 intraoral occlusal digital scans in the maximal intercuspal position of the dentition.[14,15] Then, most IOS software programs align the digital scans of the dental arches to those of the occlusion by using an implement of the iterative closest point (ICP) algorithm[16-18] (also known as best-fit), resulting in the desired digital interocclusal record (Fig. 1). The alignment can be

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Clinical Implications

The precision of different alignment methods used to obtain digital interocclusal records may differ. Clinicians should be aware that the repeatability of the method limiting the alignment to a region of interest in a dental computer-aided design software program showed statistically significant greater results than those considering complete occlusal digital scans for the alignment.

performed in few steps and requires minimal user intervention, which obfuscates the underlying complexity of the mathematical data association and iterations of the alignment process.[19] In addition, commercially available scanning software programs' best-fit algorithms are proprietary, and little information can be gathered about how the alignment is completed.[8,12] Once the alignment has been completed, both the digital scans of the dental arches and the occlusal digital scans can usually be exported in a variety of file formats for use in a third-party dental computer-aided design (CAD) software program.

However, the alignment of digital scans of the dental arches with occlusal digital scans can also be performed in dental CAD software programs. An advantage of using a dental CAD software program to perform this alignment is that the user can select which parts of the surfaces of the digital scans will be used to perform the best-fit alignment. In this way, the user can decide whether to perform a global best-fit by using all the surfaces of the digital scans or to perform a reference best-fit by using only parts of the surfaces that are considered most appropriate,[20,21] for example, the tooth surfaces that coincide in the digital scans of the dental arches and the occlusal digital scans.

Different alignment methods have been shown to lead to differing matching results.[21-24] Therefore, different alignment methods may be expected to produce different digital interocclusal records. As the alignment of the buccal scans is carried out at the initial stage of the digital workflow, the influence of the alignment method might be crucial to the accuracy of the occlusal contacts to be considered at later stages. To date, information on the accuracy of the different alignment methods used to obtain digital interocclusal records is lacking.[11-13]

The accuracy of an alignment method to obtain digital interocclusal records refers to its ability to provide correct and repeatable digital interocclusal records. According to the International Organization for Standardization (ISO) standard 5725-1,[25] accuracy is a combination of trueness and precision, with trueness referring to the ability of the alignment method to provide digital interocclusal records as close to the real one as possible and precision referring to the closeness of agreement between independent digital interocclusal records provided by the alignment method under stipulated conditions.

The purpose of this in vitro study was to evaluate the precision under repeatability conditions (repeatability) of different alignment methods to obtain digital interocclusal records. The null hypothesis was that the repeatability of different alignment methods to obtain digital interocclusal records would be the same.

MATERIAL AND METHODS

Repeatability of 3 different alignment methods to obtain digital interocclusal records was determined and compared (Fig. 2). These alignment methods were automatic alignment performed by the software program of an IOS (TRIOS 3; 3Shape A/S) (TRI method) and global and reference best-fit alignments performed in a dental CAD software program (exocad Dental CAD; exocad, GmbH) (EXO-B and EXO-R methods, respectively).

With the approval of the university ethical committee (M10_2019_254), mandibular and maxillary gypsum casts of a dentate healthy adult were scanned with the IOS as per the manufacturer's protocol (Fig. 3A, B). Gypsum casts were mounted in maximum intercuspal position in a semi-adjustable mechanical articulator (1801 AR Model PSH Articulator; Panadent Corp). Then, right and left occlusal digital scans were acquired with the IOS as per the manufacturer's instructions (Fig. 3C, D). Both occlusal digital scans were repeated 7 times under repeatability conditions.[25] To ensure repeatability conditions, the same experienced operator performed all scans in a short time interval and in a controlled laboratory environment (21 ±1 °C temperature and relative humidity of 37±3%) with only ceiling lighting (approximately 1000 lux). Immediately after the acquisition of each pair of occlusal digital scans, the software program of the IOS automatically aligned the maxillary and mandibular digital scans with the occlusal digital scans (TRI method), resulting in a digital interocclusal record (Fig. 4). Therefore, 7 digital interocclusal records were acquired, each composed of aligned maxillary and mandibular digital scans and 2 occlusal digital scans. All scans were exported in the standard tessellation language (STL) file format.

The digital scans from each digital interocclusal record were then imported separately in the dental CAD software program[26] and aligned using EXO-B and EXO-R alignment methods. The EXO-B method comprised the following steps: first, the right occlusal digital scan was aligned to the maxillary digital scan in a first stage as a prealignment by joining 4 common landmarks (Fig. 5A) and then by global best-fit (Fig. 5B); next, the left occlusal digital scan was aligned to the maxillary digital scan in a

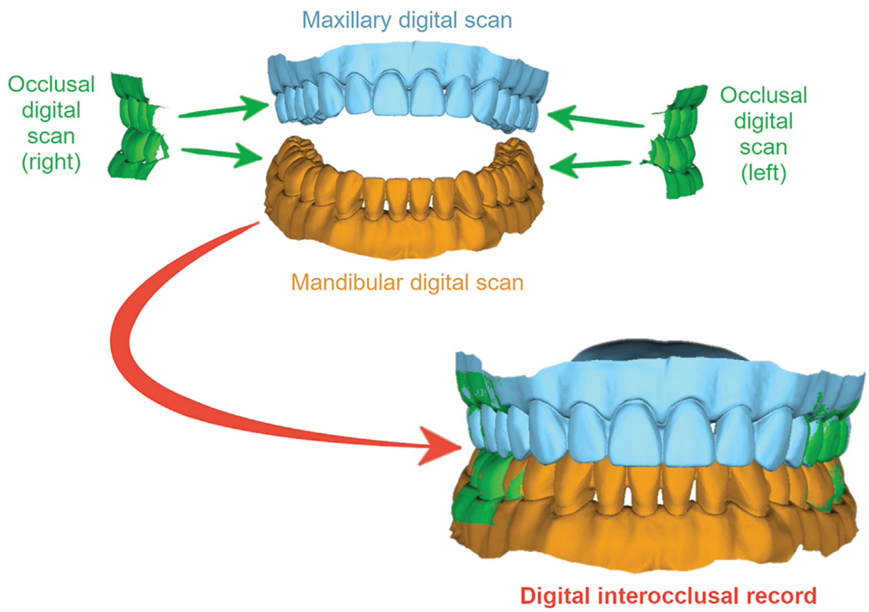

Figure 1. Acquisition of digital interocclusal records using intraoral scanner.

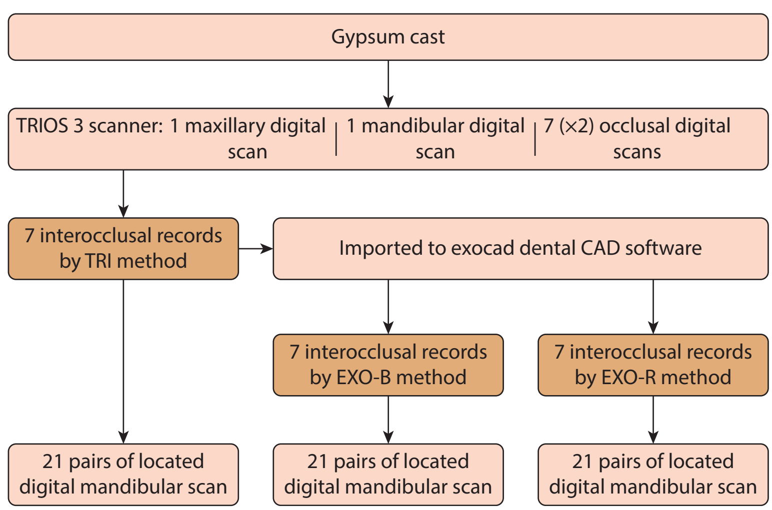

Figure 2. Flow chart of experimental design of study. EXO-B, exocad best-fit alignment; EXO-R, reference best-fit alignment; TRI, TRIOS best-fit alignment.

first stage as a prealignment by joining 4 common landmarks (Fig. 5C) and then by global best-fit (Fig. 5D); finally, the mandibular digital scan was aligned with the right and left occlusal digital scan in a first stage as a prealignment by joining 8 landmarks (Fig. 5E) and then by global best-fit (Fig. 5F). With the EXO-R alignment method, the same steps were followed, but the surfaces used to perform the best-fit alignment were restricted (Fig. 6). As a result of each alignment process, a digital interocclusal record composed of aligned maxillary and mandibular digital scans and 2 occlusal digital scans was acquired. Therefore, with each alignment method, 7 digital interocclusal records were obtained, and the digital scans from each digital interocclusal record were exported in the STL file format.

Digital interocclusal records from each group were imported in pairs in all possible nonrepeating pair combinations ($^{7}C_{2}$=21) into a 3-dimensional inspection software program (GOM Inspect 2018; GOM, GmbH). For each pair, digital interocclusal records were repositioned in a common reference system by aligning the maxillary digital scans of both records by global best-fit (being copies of the same maxillary digital scan, the alignment was performed without error) (Fig. 7). Once both digital interocclusal records had been repositioned in a common reference system, the mandibular digital scan of each was

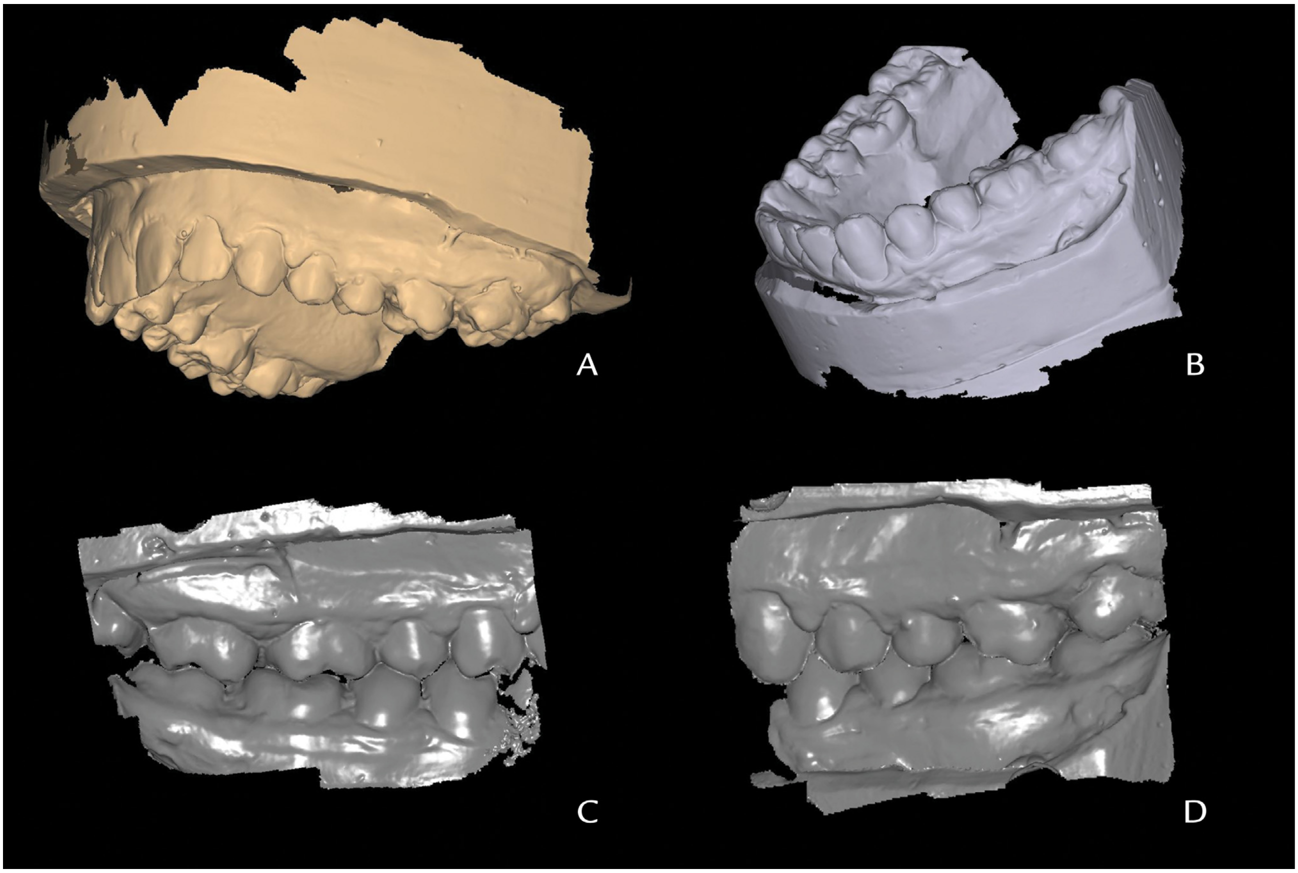

Figure 3. Digital scans acquired with intraoral scanner. A, Maxillary digital scan. B, Mandibular digital scan. C, Right occlusal digital scan. D, Left occlusal digital scan.

exported in the STL file format. Thus, 21 pairs of located mandibular digital scans were obtained for each group.

The difference between the spatial locations of each pair of mandibular digital scans was then determined by following the methodology described by Amezua et al.[27] First, a copy of the mandibular digital scan was loaded into a reverse engineering software program (Geomagic Studio 2013; Geomagic, Inc) together with a 20-mm edge cube, previously designed in an engineering CAD software program (Solid Edge; Siemens, AG). The mandibular digital scan was oriented to the cube, and the set was exported in the STL file format. Subsequently, each pair of located mandibular digital scans was imported separately into the 3-dimensional inspection software program in conjunction with 2 copies of the mandibular digital scan with cube. The mandibular digital scans with cube were then aligned to the located mandibular digital scans by best-fit, one with one and the other with the other (being copies of the same mandibular digital scan, the alignments were performed without error) (Fig. 8). Afterward, a coordinate system was created on each of the mandibular digital scans by the attached cube (Fig. 9): the coordinate system $(O_A XYZ)_A$ on one and the coordinate system $(O_B UVW)_B$ on the other. Then, the homogeneous transformation matrix that defines the location of coordinate system $(O_B UVW)_B$ with respect to coordinate system $(O_A XYZ)_A$ was determined, and the vertex-to-vertex distances d_P were calculated as

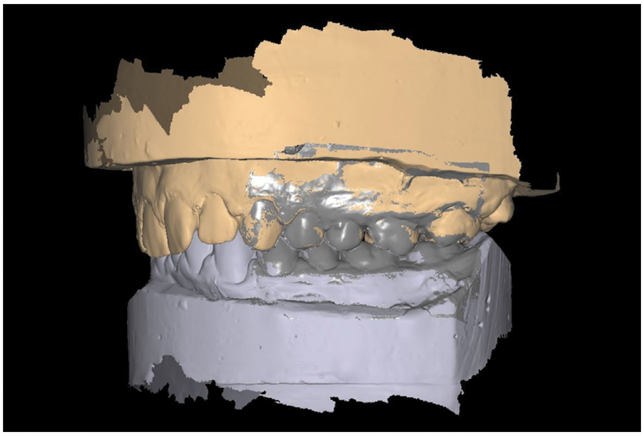

Figure 4. Digital interocclusal record provided by intraoral scanner software program.

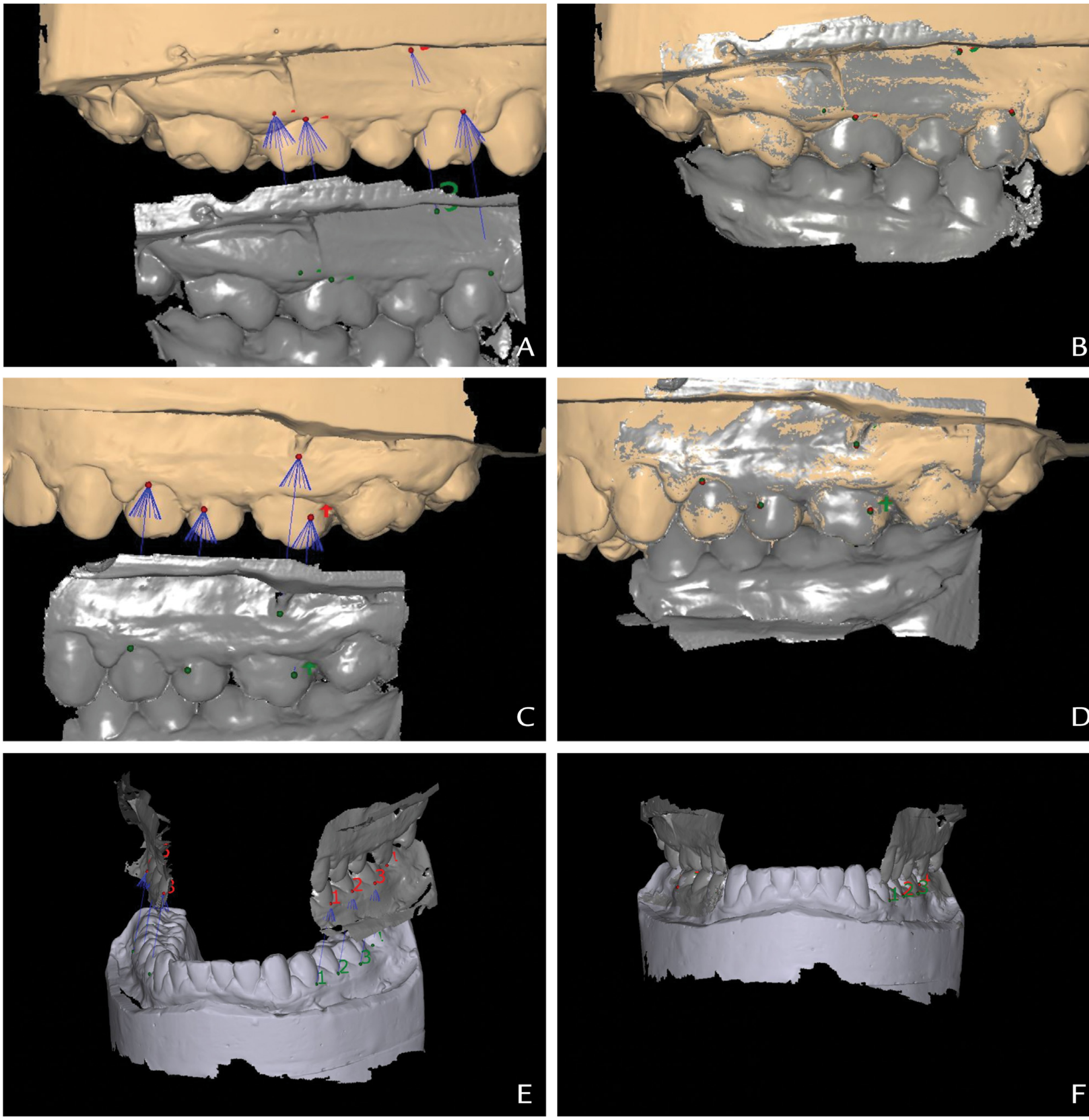

Figure 5. Global best-fit alignment method. A, Prealignment of right occlusal digital scan to maxillary digital scan by matching 4 common landmarks. B, Alignment of right occlusal digital scan to maxillary digital scan by global best-fit. C, Prealignment of left occlusal digital scan to maxillary digital scan by matching 4 common landmarks. D, Alignment of left occlusal digital scan to maxillary digital scan by global best-fit. E, Prealignment of mandibular digital scan to right and left occlusal digital scans by matching 8 common landmarks. F, Alignment of mandibular digital scan to right and left occlusal digital scans by global best-fit.

described by Amezua et al,[27] resulting in 181 099 vertex-to-vertex distances for each pair (Fig. 9).

All sets of vertex-to-vertex distances were then loaded into a statistical software program (IBM SPSS Statistics, v26; IBM Corp) to determine and compare the repeatability of the 3 alignment methods. For that, the mean vertex-to-vertex distance of each set of distances was calculated (Fig. 10). Then, the repeatability of each alignment method was determined in terms of mean vertex-to-vertex distances within each group and expressed, in turn, as their median with interquartile range (IQR) (Table 1) given that the Shapiro-Wilk test (α=.05) revealed that a normal distribution of mean vertex-to-vertex distances could not be assumed for all groups. Finally, the repeatability of the different alignment methods was compared by means of the Kruskal-

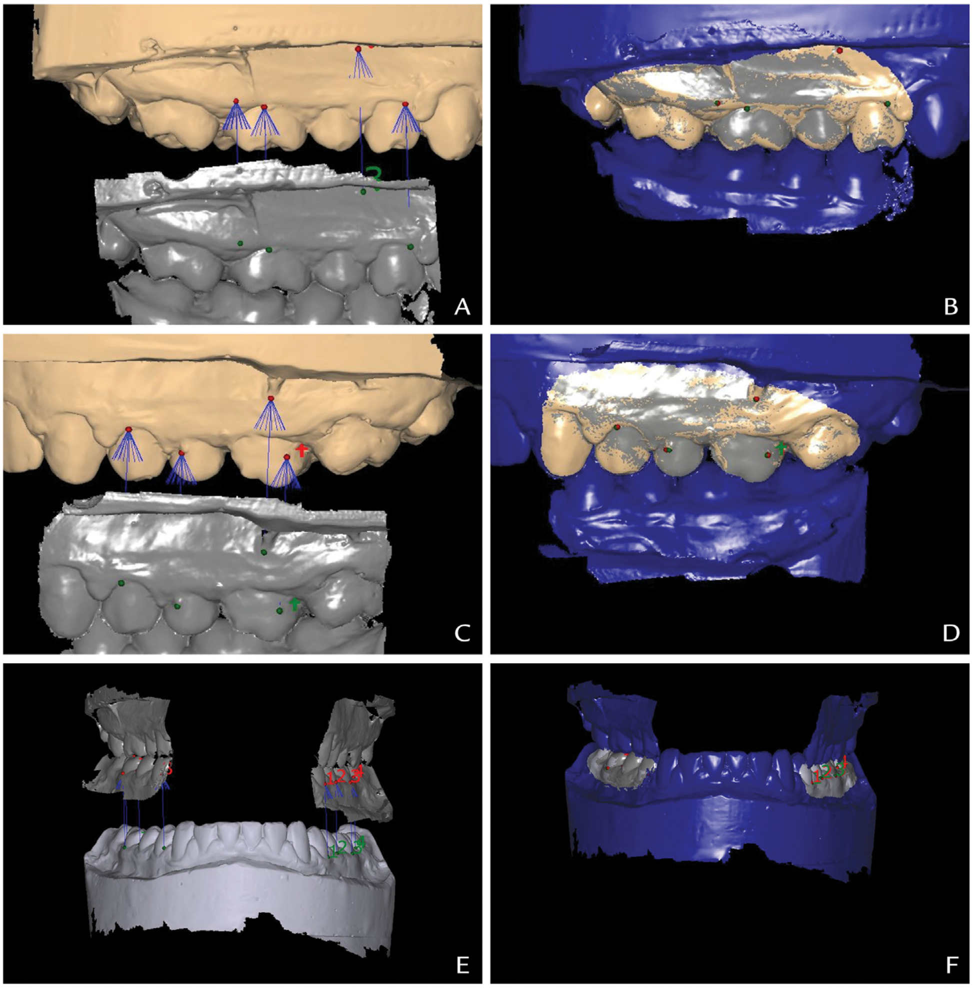

Figure 6. Reference best-fit alignment method. A, Prealignment of right occlusal digital scan to maxillary digital scan by matching 4 common landmarks. B, Alignment of right occlusal digital scan to maxillary digital scan by reference best-fit (*blue* = surfaces excluded for reference best-fit alignment). C, Prealignment of left occlusal digital scan to maxillary digital scan by matching 4 common landmarks. D, Alignment of left occlusal digital scan to maxillary digital scan by reference best-fit (*blue* = surfaces excluded for alignment). E, Prealignment of mandibular digital scan to right and left occlusal digital scans by matching 8 common landmarks. F, Alignment of mandibular digital scan to right and left occlusal digital scans by reference best-fit (*blue* = surfaces excluded for alignment).

Wallis test and the post hoc Dunn test with Bonferroni adjustment (both α=.05) (Table 2).

RESULTS

Table 1 shows the repeatability of the 3 alignment methods used to obtain the digital interocclusal records analyzed. The maximum distances between the median values of alignment methods were 80 µm for the TRI method, 69 µm for the EXO-B method, and 21 µm for the EXO-R method (Fig. 10). The Kruskal-Wallis test detected a statistically significant difference between the repeatability of the alignment methods (P<.05). The Dunn-Bonferroni pairwise comparisons revealed that the repeatability of the EXO-R alignment method was statistically different (P<.001) compared with the EXO-B and TRI

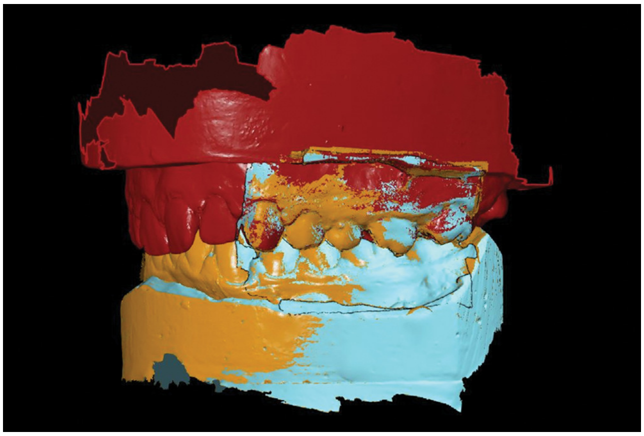

Figure 7. Repositioning of digital interocclusal digital records in common reference system by aligning maxillary digital scans using global best-fit (*red* = surfaces used for best-fit alignment).

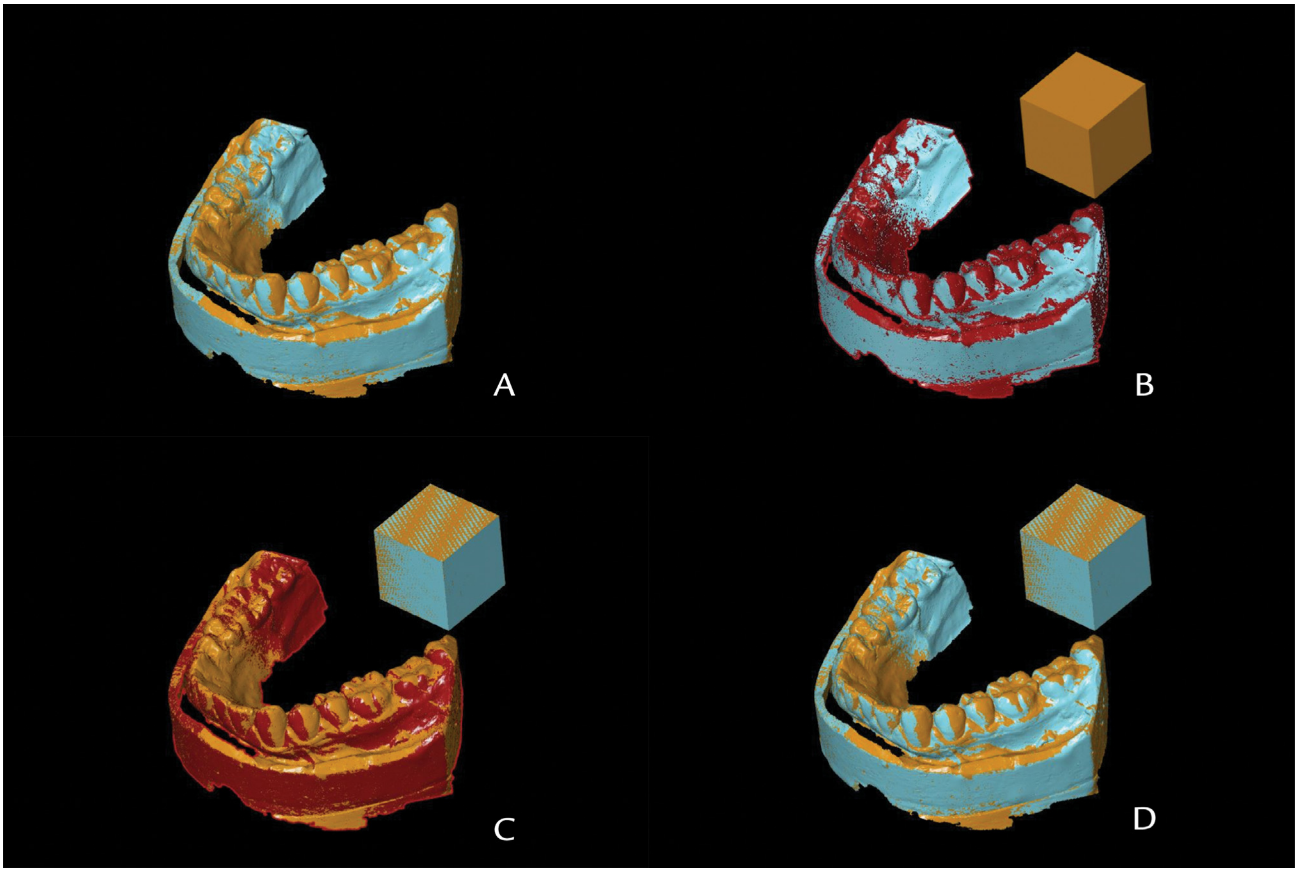

Figure 8. Replacement of pair of mandibular digital scans with pair of mandibular digital scans with cube. A, Pair of mandibular scans to replace. B, Alignment of mandibular digital scan with cube to orange colored located mandibular digital scan (*red* = surfaces used for best-fit alignment). C, Alignment of mandibular digital scan with cube to blue-colored located mandibular digital scan (*red* = surfaces used for best-fit alignment). D, Located mandibular digital scans replaced by mandibular digital scans with cube.

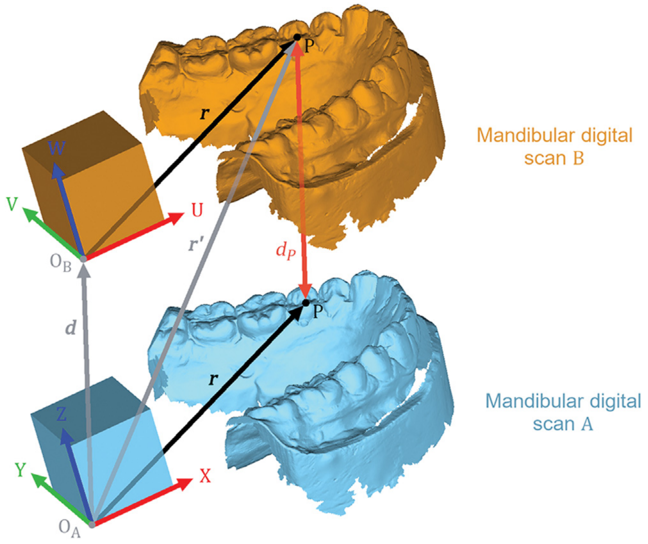

Figure 9. Schematic of vertex-to-vertex distance calculation.

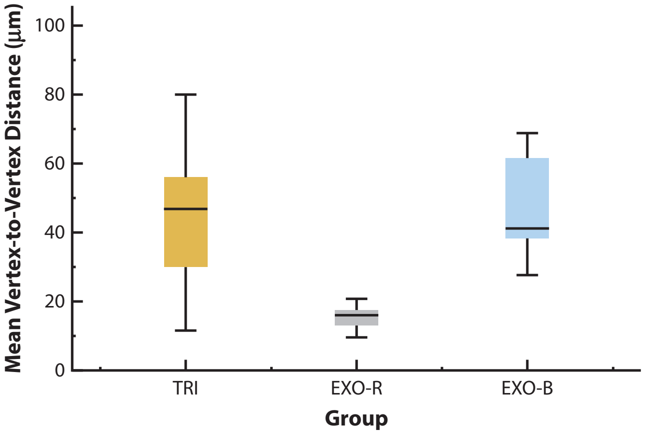

Figure 10. Box plot of distance data distribution. EXO-B, exocad best-fit alignment; EXO-R, reference best-fit alignment; TRI, TRIOS best-fit alignment.

alignment methods, while the repeatability between the EXO-B and TRI alignment methods was not statistically significantly different (*P*>.05) (Table 2).

DISCUSSION

The null hypothesis that the repeatability of different alignment methods to obtain digital interocclusal records was the same was rejected, since statistically significant

Table 1. Descriptive statistics of mean vertex-to-vertex distances of distance sets obtained in each group

Group	Median (μm)	IQR (μm)
TRI	47	27
EXO-R	16	5
EXO-B	41	25

IQR, interquartile range.

Table 2. Mean vertex-to-vertex distance comparison between groups with post hoc Dunn-Bonferroni test

Groups	*P*
EXO-R–TRI	<.001
EXO-R–EXO-B	<.001
TRI–EXO-B	1

differences were detected for some of the analyzed methods. The results indicated that the repeatability of the EXO-R alignment method was better than that of the EXO-B and TRI methods. The spread of values of the EXO-R method was the narrowest as reflected in the IQR (5 μm). However, a significant difference was not found between the repeatability of the EXO-B and TRI methods, and the IQR of both was similar (25 μm for EXO-B and 27 μm for TRI).

The EXO-R method reduced the distortion of the distance of the aligned vertices under repeatability by a factor of 3 with respect to the EXO-B and TRI methods on average and was consistent with a previous investigation.[19] When the EXO-R alignment method was performed, the selected region was limited to the essential points that influence the alignment error and thus improve its accuracy.[16] Similarly, if the selection was extended to the whole scan set, the probability of introducing noise increased, affecting the degree of overlapping.[17,18]

Previous studies that investigated the digital workflow using an IOS to reproduce the dimensional relationship of mandibular and maxillary teeth are scarce[9,10,12,13] and do not explicitly consider the choice of alignment method, although alignment has been limited to a region of interest.[8] Therefore, a quantitative comparison among studies was not possible because of methodological heterogeneity. Nevertheless, considering that the maximum distortion of the average distances of the TRI method reached 80 μm in the present investigation, further studies should consider the alignment method.

Limitations of the present study included that the EXO-R alignment method introduced operator influence when selecting the region of interest. In the same way, in the present study, a broadly evaluated IOS[5-7,12] and 2 popular software programs[28] were selected, and further analysis is needed to determine whether the alignment disparities are repeated in other software programs. In addition, the current study focused on the precision of the alignment under repeatability conditions to compare the results in the most favorable conditions and to conclude whether they are statistically significant. The clinical consequences of this study may be affected by introducing environmental factors such as patient movements, saliva, or interference from soft tissues.

CONCLUSIONS

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

1. The alignment method influenced repeatability in obtaining digital interocclusal records.
2. The repeatability of alignment was statistically significantly greater in the EXO-R method than in the EXO-B and TRI methods. Therefore, reference best-fit alignment (consisting of the selection of the region of interest) was a better alignment method to obtain digital interocclusal records.
3. No significant difference was found in the repeatability of alignment provided by the EXO-B and TRI methods.

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Xabier Garikano: Conceptualization, Methodology, Software, Investigation, Writing – original draft. **Xabier Amezua:** Investigation, Writing – original draft, Visualization. **Mikel Iturrate:** Formal analysis, Data curation, Visualization. **Eneko Solaberrieta:** Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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