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Analysis of the impact of the facial scanning method on the precision of a virtual facebow record technique: An in vivo study

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ABSTRACT

Statement of problem. Virtual facebow record techniques typically record the relationship of a maxillary digital scan to facial landmarks by aligning it to a 3-dimensional face scan. Three-dimensional face scans can be acquired with different facial scanning methods, but the impact of the facial scanning method on the accuracy (trueness and precision) of a virtual facebow record technique remains unclear.

Purpose. The purpose of this in vivo study was to assess the impact of the facial scanning method on the precision under the repeatability conditions (repeatability) of a virtual facebow record technique.

Material and methods. Repeatability of the virtual facebow record technique with the following 3 clinical-grade facial scanning methods was determined and compared: a professional handheld scanner based on structured blue light scanning technology (PHS method); an attachment-type 3-dimensional sensor camera connected to a tablet and controlled with a mobile application (3DSC-T method); and a smartphone with an integrated 3-dimensional sensor camera controlled with a mobile application (3DSC-S method). To determine the repeatability of the virtual facebow record technique with each facial scanning method, 8 virtual facebow records of a completely dentate adult with class I occlusion and mesoprosopic facial form were obtained (8×3=24 in total); with these, 8 locations of a maxillary digital scan with respect to a common 3-dimensional face scan were obtained. Repeatability was determined in terms of deviations between located maxillary digital scans, determined, in turn, by calculating the distances between corresponding vertices for each of the possible nonrepeating combinations of pairs of located maxillary digital scans ($^{8}C_{2}$=28). Finally, the repeatability of the virtual facebow record technique with the different facial scanning methods was compared by using the Welch ANOVA test and the post hoc Games-Howell test (both α=.05).

Results. The repeatability of the virtual facebow record technique with PHS, 3DSC-T, and 3DSC-S facial scanning methods resulted in 0.243 ±0.094 mm, 0.437 ±0.171 mm, and 1.023 ±0.399 mm, respectively. Comparison of these results revealed that the facial scanning method had a statistically significant effect on the repeatability of the virtual facebow record technique (*P*<.001) and that its repeatability was statistically significantly greater with the PHS facial scanning method than with the 3DSC-T and 3DSC-S facial scanning methods and greater with the 3DSC-T facial scanning method than with the 3DSC-S facial scanning method (*P*<.001 for all pairwise comparisons).

Conclusions. This study found that the facial scanning method had a great impact on the repeatability of the virtual facebow record technique and that the virtual facebow record technique was more repeatable with more accurate facial scanning methods. (J Prosthet Dent 2023;130:382-91)

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Clinical Implications

The facial scanning method had a great impact on the ability of a virtual facebow record technique to provide repeatable locations of a maxillary digital scan with respect to a 3-dimensional face scan. Clinicians need to be aware of this when selecting the facial scanning method.

In dental computer-aided design and computer-aided manufacturing (CAD-CAM) systems, virtual articulators are used to substitute or complement mechanical articulators.[1] As most of these virtual articulators have structures and working principles similar to those of mechanical articulators, adequate mounting of digital scans of dental arches is a prerequisite for simulating individual jaw movements as realistically as possible. Therefore, several techniques for mounting digital scans of dental arches to virtual articulators have been developed,[2] including virtual facebow (VF) techniques.[3-9]

A VF technique is a digital alternative to a facebow and as such is used to mount a maxillary digital scan to a virtual articulator according to the relationship of the maxillary arch to some anatomic reference point or points. The most used VF techniques consist firstly of recording the relationship of the maxillary digital scan to some facial landmarks and then mounting it on the virtual articulator according to this relationship.[7-9] To obtain such a relationship, a VF record that involves aligning the maxillary digital scan to one or more 3-dimensional (3D) face scans is made. Therefore, an accurate mounting of a maxillary digital scan in a virtual articulator through these VF techniques requires, among other things, an accurate VF record. Different VF record techniques are available,[7-15] but their accuracy has been little studied.[16-18]

The accuracy of a VF record technique refers to its ability to provide correct and repeatable locations of a maxillary digital scan with respect to a 3D face scan. According to the International Organization for Standardization (ISO) standard 5725-1,[19] accuracy is a combination of trueness and precision, with trueness referring to the ability of the VF record technique to locate a maxillary digital scan to a 3D face scan as close to its real position as possible and precision to the closeness of agreement between independent locations of a maxillary digital scan to a 3D face scan provided by the VF record technique under stipulated conditions. In this regard, a previous in vitro study found that the accuracy of a VF record technique was strongly influenced by the facial scanning method used and that the VF record technique was more accurate, with more accurate facial scanning methods.[18]

Previous studies have evaluated the accuracy of different facial scanning methods, concluding that the most accurate are stationary facial scanning systems based on stereophotogrammetry scanning technology.[20,21] However, their cost, size, complexity, and lack of portability may limit the clinical adoption of these systems.[20,21] Alternatively, professional handheld scanners, whose accuracy has been shown to be comparable with those of stationary facial scanning systems, are available.[22-24] Low-cost and easy-to-use alternatives are also available,[25,26] including 3D sensor cameras based on structured light scanning technology.[26-28] Initially, these 3D sensor cameras were of the accessory type and were connected to smartphones, tablets, or laptop computers.[26,27] However, more recently, these 3D sensor cameras have also been integrated into some smartphones and tablets.[28] The accuracy of these 3D sensor cameras is not comparable with that of professional handheld scanners but has been reported to be clinically acceptable.[21,28] Nevertheless, the accuracy of VF record techniques with these clinical-grade facial scanning methods remains unclear.

The purpose of this in vivo study was to assess the impact of the facial scanning method on the precision under repeatability conditions (repeatability) of a VF record technique. The null hypothesis was that no difference would be found in the repeatability of the VF record technique when using different facial scanning methods.

MATERIAL AND METHODS

Repeatability of a VF record technique (AFT System One; AFT Dental System, SL) with 3 different clinical-grade facial scanning methods was determined and compared. The selected 3 facial scanning methods were a professional handheld scanner based on structured blue light scanning technology (Artec Space Spider; Artec 3D, SARL) (PHS method); an attachment-type 3D sensor camera (Bellus3D Face Camera Pro; Bellus3D, Inc) connected to a tablet (Huawei MediaPad M3; Huawei Technologies Co, Ltd) and controlled with a mobile application (Bellus3D Face Camera App; Bellus3D, Inc) (3DSC-T method); and a smartphone with an integrated 3D sensor camera (iPhone X; Apple, Inc) controlled with a mobile application (Bellus3D FaceApp; Bellus3D, Inc) (3DSC-S method).

A completely dentate 22-year-old man with class I occlusion and mesoprosopic facial form was recruited. The study was approved by the university ethical committee (M10_2019_254), and according to local and international ethical rules, the participant signed an informed consent form before enrollment in the study.

An intraoral scan of the participant's maxillary arch was made by using an intraoral scanner (TRIOS 3; 3Shape A/S) by following the manufacturer's scanning

Figure 1. Maxillary digital scan.

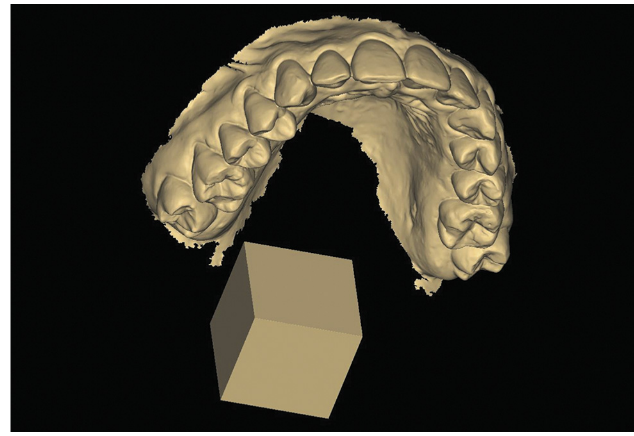

Figure 2. Maxillary digital scan aligned to cube.

strategy. This was performed by an experienced operator, with the participant positioned in a dental chair at a research laboratory with only ceiling lighting. A maxillary digital scan was obtained in the standard tessellation language (STL) file format (Fig. 1), which was then loaded into a reverse engineering software program (Geomagic Studio 2013; Geomagic, Inc) in conjunction with a 20-mm edge cube, previously designed by using an engineering CAD software program (Solid Edge; Siemens AG). The maxillary digital scan was oriented with respect to the cube, and the set was exported in the STL file format for subsequent use (Fig. 2).

An intraoral transfer element (IOTE) and a facial transfer element (FTE) were then placed on the participant: the FTE on the participant's forehead, well centered, and the IOTE in the participant's mouth, attached firmly to the lip and stabilized with high- and low-viscosity polyvinyl siloxane impression material (Aquasil Soft Putty and Aquasil Ultra LV; Dentsply Sirona). In addition, a small point was drawn on the participant's nose with an ultrafine, black permanent marker (BIC Marking; BIC, Inc) by following the bipupillary line as a reference.

With the FTE and IOTE in place, 8 repeated facial scans were made with each of the 3 facial scanning methods (Fig. 3). All scans were performed with the participant seated in an adjustable rotary chair, and, to ensure repeatability conditions, they were performed by the same experienced operator in the same research laboratory and within a short time, leaving a few seconds between scans and changing the facial scanning method in random order after every 4 scans. Scans with the PHS method were performed by moving the scanner manually around the participant's face at a distance of between 20 and 30 cm, and, in contrast with the 3DSC-T and 3DSC-S methods, by positioning the corresponding mobile device (the tablet with the 3D sensor camera attached and the smartphone, respectively) on a fixed support at a distance of between 30 and 45 cm from the participant's face and by rotating the chair according to the instructions given by the mobile application. Each scan with the PHS method took approximately 40 seconds, whereas with the 3DSC-T and 3DSC-S methods, 20 seconds. As a result, 24 3D face scans (named reference face scans) were obtained in the object (OBJ) file format (Fig. 3B, D, F).

Subsequently, the IOTE was removed from the mouth, maintaining the FTE in the same position. Then, a facial scan was performed with the participant at the rest position by using each of the 3 facial scanning methods (Fig. 4). This resulted in three 3D face scans (named rest face scans) in the OBJ file format (Fig. 4B, D, F). The IOTE was then scanned by using a laboratory scanner (E2; 3Shape A/S). For that, the impression area was coated with scanning powder (Spray Scan Schmidt Line; Henry Schein, Inc). As a result, the digital scan of the IOTE was obtained in the STL file format (Fig. 5).

After completion of all scans, the participant's VF records were obtained. For that, each of the 8 reference face scans acquired with each of the 3 facial scanning methods was imported separately into a dental CAD software program (exocad; exocad GmbH) in conjunction with the rest face scan acquired with the same facial scanning method, the maxillary digital scan, and the digital scan of the IOTE. There, the maxillary digital scan was aligned to the rest face scan, keeping the rest face scan fixed. This was accomplished by following the alignment procedure established by the VF record technique in reverse order (Fig. 6): first, the reference face scan was aligned to the rest face scan (Fig. 6A); then, the digital scan of the IOTE was aligned to the reference face scan (Fig. 6B); and finally, the maxillary digital scan was aligned to the digital scan of the IOTE (Fig. 6C). Thus, 3 groups of 8 repeated VF records were obtained, which were named according to the facial scanning method used to obtain

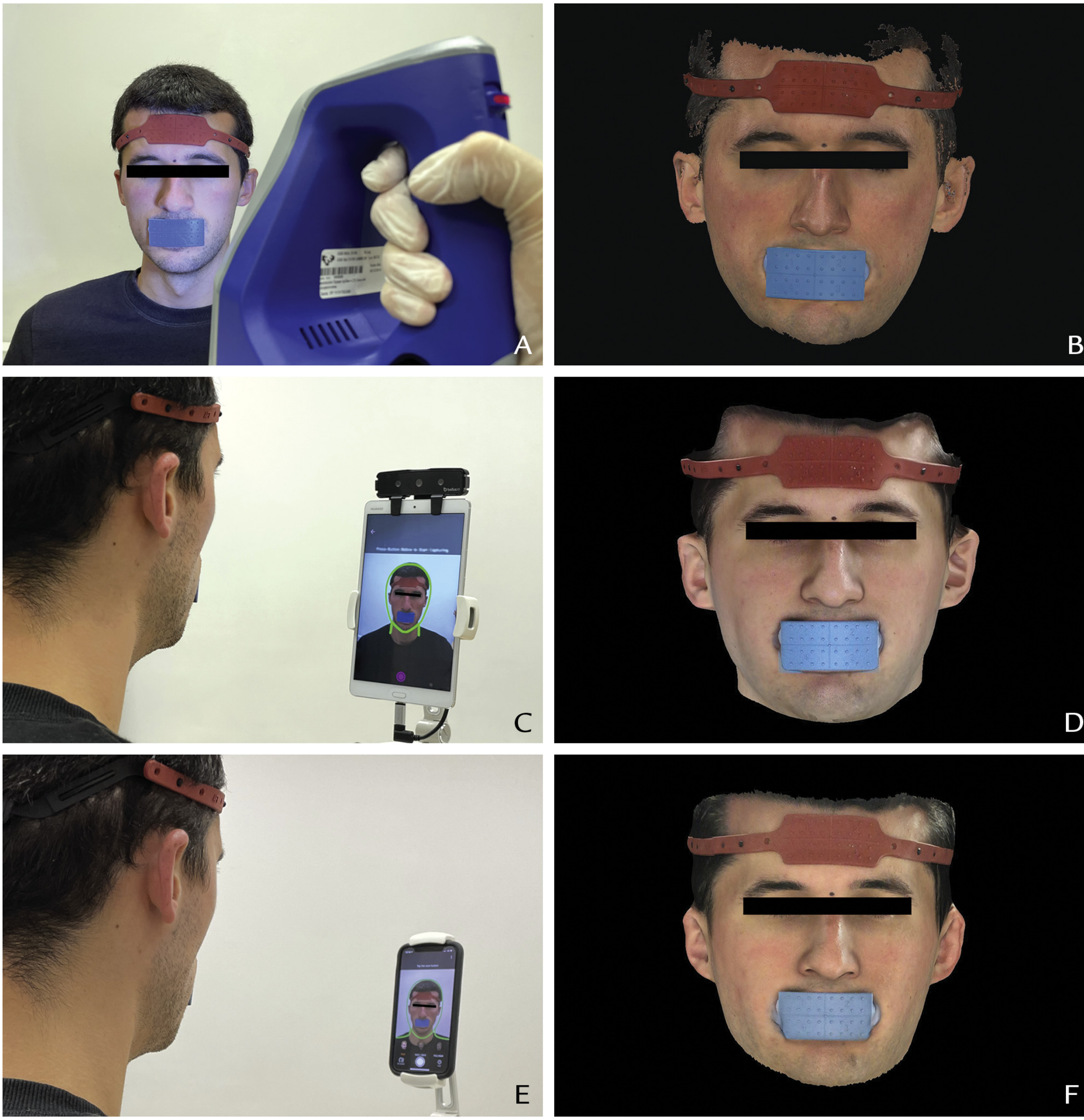

Figure 3. Acquisition of reference face scans with different facial scanning methods. A, Reference facial scan with PHS facial scanning method. B, Reference face scan acquired with PHS facial scanning method. C, Reference facial scan with 3DSC-T facial scanning method. D, Reference face scan acquired with 3DSC-T facial scanning method. E, Reference facial scan with 3DSC-S facial scanning method. F, Reference face scan acquired with 3DSC-S facial scanning method.

the 3D face scans: PHS, 3DSC-T, and 3DSC-S. In this way, in each of the 8 VF records belonging to the same group, a spatial location of the maxillary digital scan was obtained with respect to a common rest face scan. From each VF record, the located maxillary digital scan was exported in the STL file format. In each group, each located maxillary digital scan was labeled as VFR_i (i=1 to 8).

Then, for each group, the deviation between pairs of located maxillary digital scans was determined for all possible pair combinations without repetition ($^{8}C_{2}=28$). To determine the deviation between a pair of located maxillary digital scans, given that a maxillary digital scan is a polygonal mesh and that the located maxillary digital scans are copies of the same maxillary digital scan at different spatial locations, distances between

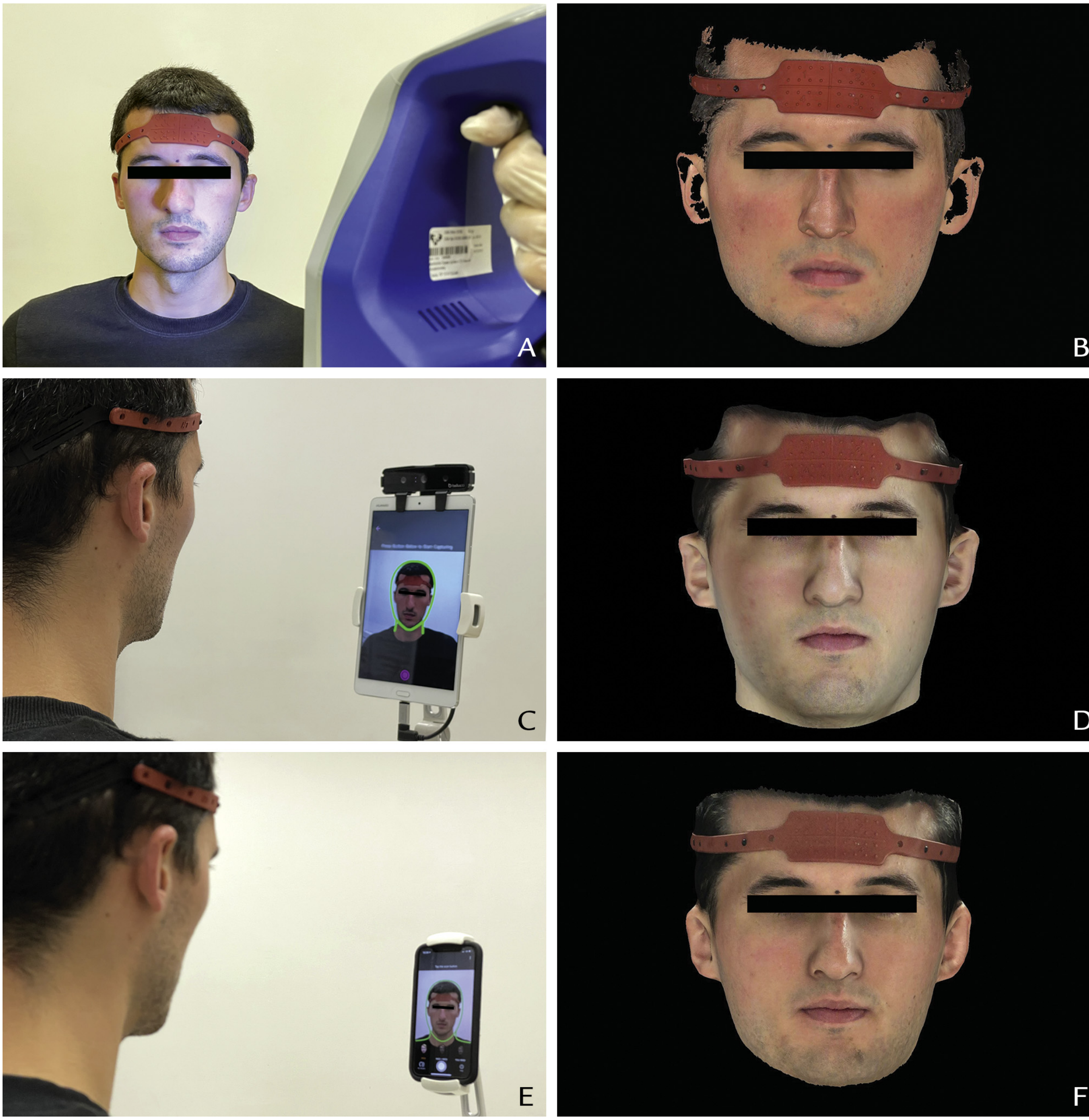

Figure 4. Acquisition of rest face scans with different facial scanning methods. A, Rest facial scan with PHS facial scanning method. B, Rest face scan acquired with PHS facial scanning method. C, Rest facial scan with 3DSC-T facial scanning method. D, Rest face scan acquired with 3DSC-T facial scanning method. E, Rest facial scan with 3DSC-S facial scanning method. F, Rest face scan acquired with 3DSC-S facial scanning method.

corresponding vertices were calculated as a distance map by using the methodology described by Amezua et al.[18] According to this methodology, each pair of located maxillary digital scans was loaded separately into a 3D inspection software program (GOM Inspect 2019; GOM GmbH). There, a coordinate system was created on each by using the attached cube (Fig. 7): the coordinate system $(O_AXYZ)_A$ on one (hereinafter located maxillary digital scan *A*) and the coordinate system $(O_BUVW)_B$ on the other (hereinafter located maxillary digital scan *B*). Once the coordinate systems were created, the components of the homogeneous transformation matrix ${}^{A}_{B}T$ that defines the location of the coordinate system $(O_BUVW)_B$ with respect to the coordinate system $(O_AXYZ)_A$ were

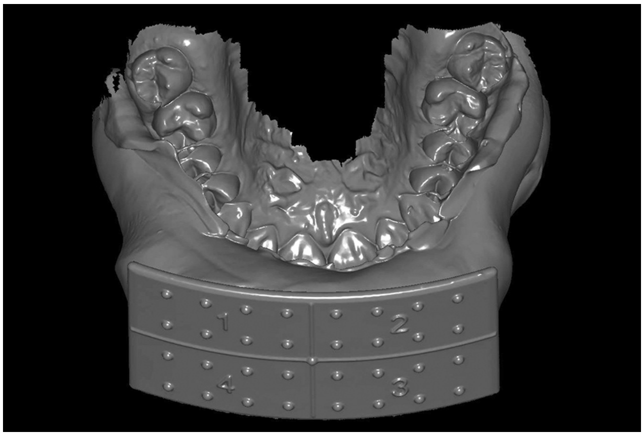

Figure 5. Digital scan of IOTE. IOTE, intraoral transfer element.

obtained: $${}^{A}_{B}T = \begin{bmatrix} c(U,X) & c(V,X) & c(W,X) & d_x \\ c(U,Y) & c(V,Y) & c(W,Y) & d_y \\ c(U,Z) & c(V,Z) & c(W,Z) & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix},$$
where d_x, d_y, and d_z represent the components of the vector d linking the origin of the coordinate system $(O_A XYZ)_A$ with the origin of the coordinate system $(O_B UVW)_B$ and the $c(j, k)$ (j=U, V, W and k=X, Y, Z) represent the cosines of the angles formed by the axes U, V, and W of the coordinate system $(O_B UVW)_B$ with each of the axes X, Y, and Z of the coordinate system $(O_A XYZ)_A$. Afterward, the r_x, r_y, and r_z components of the position vector r of each of the 144 156 P vertices of the located maxillary digital scan A (among which the vertices corresponding to the cube were not included) were exported (Fig. 7) in American standard code for information interchange (ASCII) file format. This file was then loaded into a spreadsheet software program (Microsoft Excel; Microsoft Corp), where the following system of matrix equations was applied to each of the position vectors r of the vertices of the located maxillary digital scan A to obtain the r'_x, r'_y, and r'_z components of the position vector r' of their corresponding vertices of the located maxillary digital scan B with respect to the $(O_A XYZ)_A$ coordinate system (Fig. 7): $$\begin{Bmatrix} r'_x \\ r'_y \\ r'_z \\ 1 \end{Bmatrix} = {}^{A}_{B}T \begin{Bmatrix} r_x \\ r_y \\ r_z \\ 1 \end{Bmatrix}.$$
Once all the position vectors r' were obtained, the distance map was obtained by calculating the Euclidean distances d_P between the corresponding vertices (Fig. 7). Thus, repeating this methodology for all pairs of located maxillary digital scans, 28 distance maps were obtained for each group, each comprising 144 156 distances (Fig. 8).

The distance data were loaded into a statistical software program (IBM SPSS Statistics, v26; IBM Corp). There, the repeatability of the VF record technique with different facial scanning methods was determined and compared. For that, in each group, the mean of vertex-to-vertex distances was calculated for each distance map (Fig. 9). The repeatability of the VF record technique with each facial scanning method was determined in terms of mean vertex-to-vertex distances within each group and expressed, in turn, as their mean ±standard deviation (Table 1) because the Shapiro-Wilk test (α=.05) revealed that in each group the mean vertex-to-vertex distances were normally distributed. To compare the repeatability of the VF record technique (dependent variable) with different facial scanning methods (independent variable), the Welch ANOVA and the post hoc Games-Howell test (both α=.05) (Table 2) were used, as, despite the assumption of normality being met, the Levene test (α=.05) showed that homogeneity of variances could not be assumed. In addition, Games-Howell pairwise comparisons that detected a statistically significant difference were accompanied by Cohen d effect size measure, which determined the magnitude of such a difference (Table 2).[29] A post hoc power analysis was also performed in another statistical software program (R 4.04; R Foundation for Statistical Computing) to assess whether the sample size (n=28) was adequate to test the null hypothesis.[30]

RESULTS

The deviations between the repeated locations of the maxillary digital scan provided by the VF record technique with the PHS, 3DSC-T, and 3DSC-S facial scanning methods ranged from 0.041 mm to 0.550 mm, from 0.092 mm to 0.962 mm, and from 0.219 mm to 3.074 mm, respectively (Fig. 8). With these deviations, the repeatability of the VF record technique with the PHS, 3DSC-T, and 3DSC-S facial scanning methods resulted in 0.243 ±0.094 mm, 0.437 ±0.171 mm, and 1.023 ±0.399 mm, respectively (Table 1).

The Welch ANOVA test detected that the facial scanning method used had a statistically significant effect on the repeatability of the VF record technique (Welch's F [2, 45.226]= 58.652, P<.001), whereas the post hoc power analysis revealed a test power value equal to 1, confirming that the sample size (n=28) was adequate to test the null hypothesis. The Games-Howell post hoc test indicated that the repeatability of the VF record technique was statistically significantly greater with the PHS facial scanning method than with the 3DSC-T and 3DSC-S scanning methods and with the 3DSC-T scanning method than with the 3DSC-S scanning method (Table 2). Furthermore, according to the Cohen d measure of effect size, the magnitude of the statistically

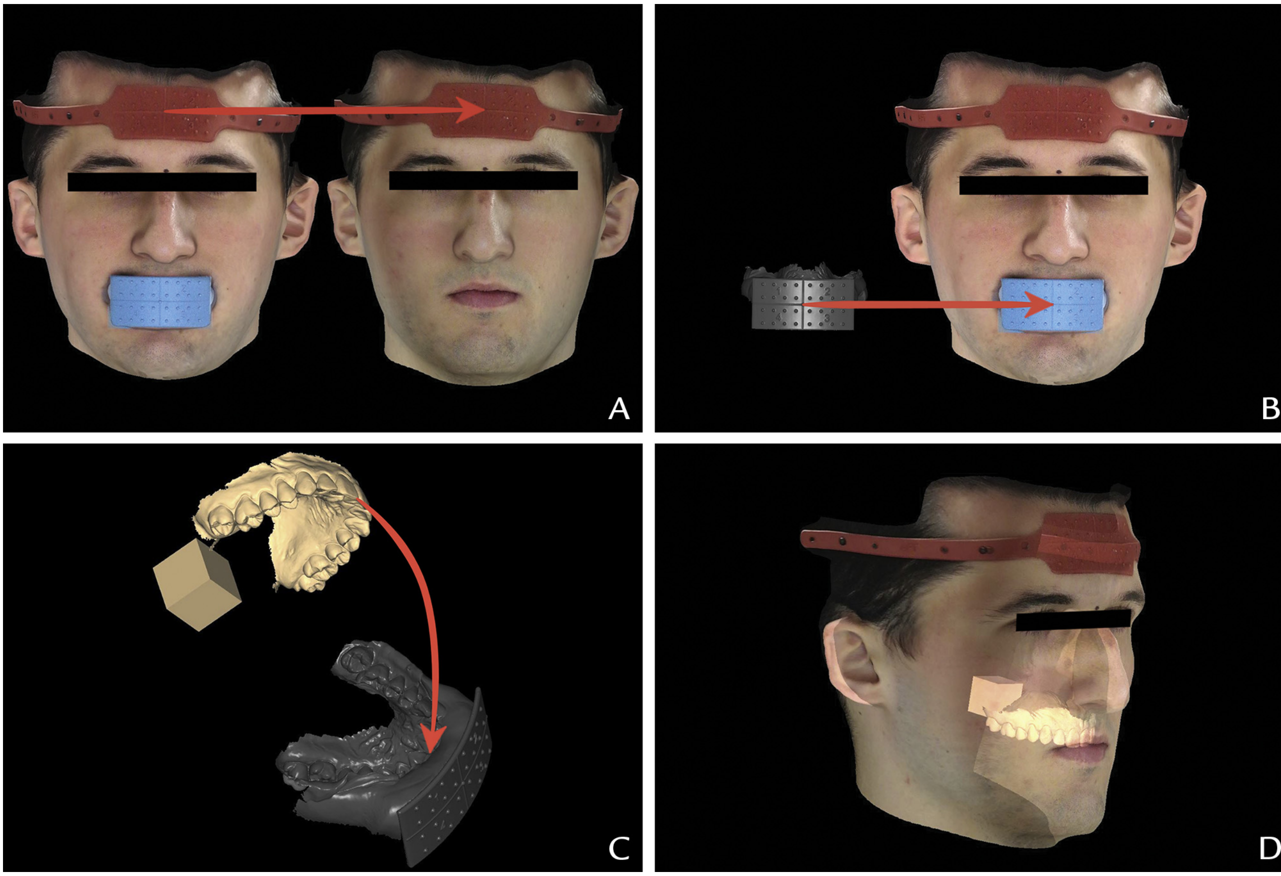

Figure 6. Alignment of maxillary digital scan to rest face scan. A, Alignment of reference face scan to rest face scan. B, Alignment of digital scan of IOTE to reference face scan. C, Alignment of maxillary digital scan to digital scan of IOTE. D, Result of alignment.

significant difference detected in these 3 pairwise comparisons was very large (d>0.8) (Table 2).[29]

DISCUSSION

The results indicated that the repeatability of the VF record technique was different with different facial scanning methods, with statistical significance; hence, the null hypothesis was rejected. The results also indicated that the repeatability of the VF record technique was statistically significantly greater with the PHS facial scanning method than with the 3DSC-T and 3DSC-S facial scanning methods and with the 3DSC-T facial scanning method than with the 3DSC-S facial scanning method (Tables 1 and 2).

Previous studies have also analyzed the repeatability of this type of VF record technique,[17,18] but a quantitative comparison among studies is not possible because of methodological heterogeneity. Nevertheless, the results obtained in the present study were consistent with those of a previous study[18] because they revealed that the facial scanning method had a great impact on the

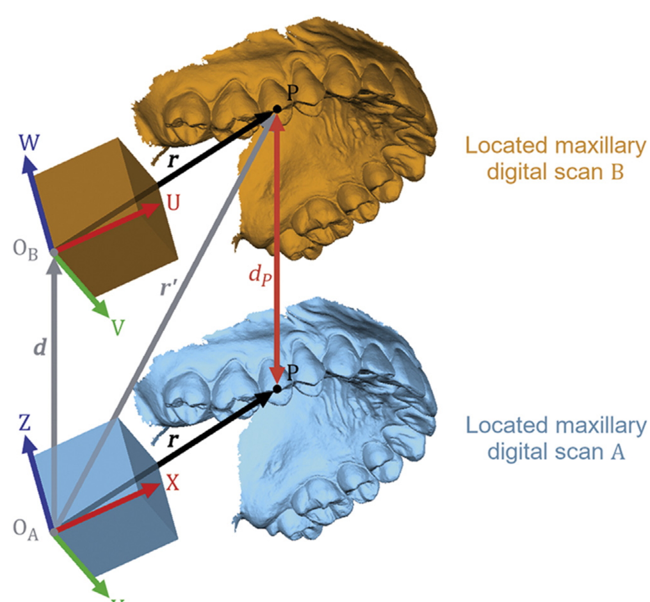

Figure 7. Schematic of calculation of distances between corresponding vertices.

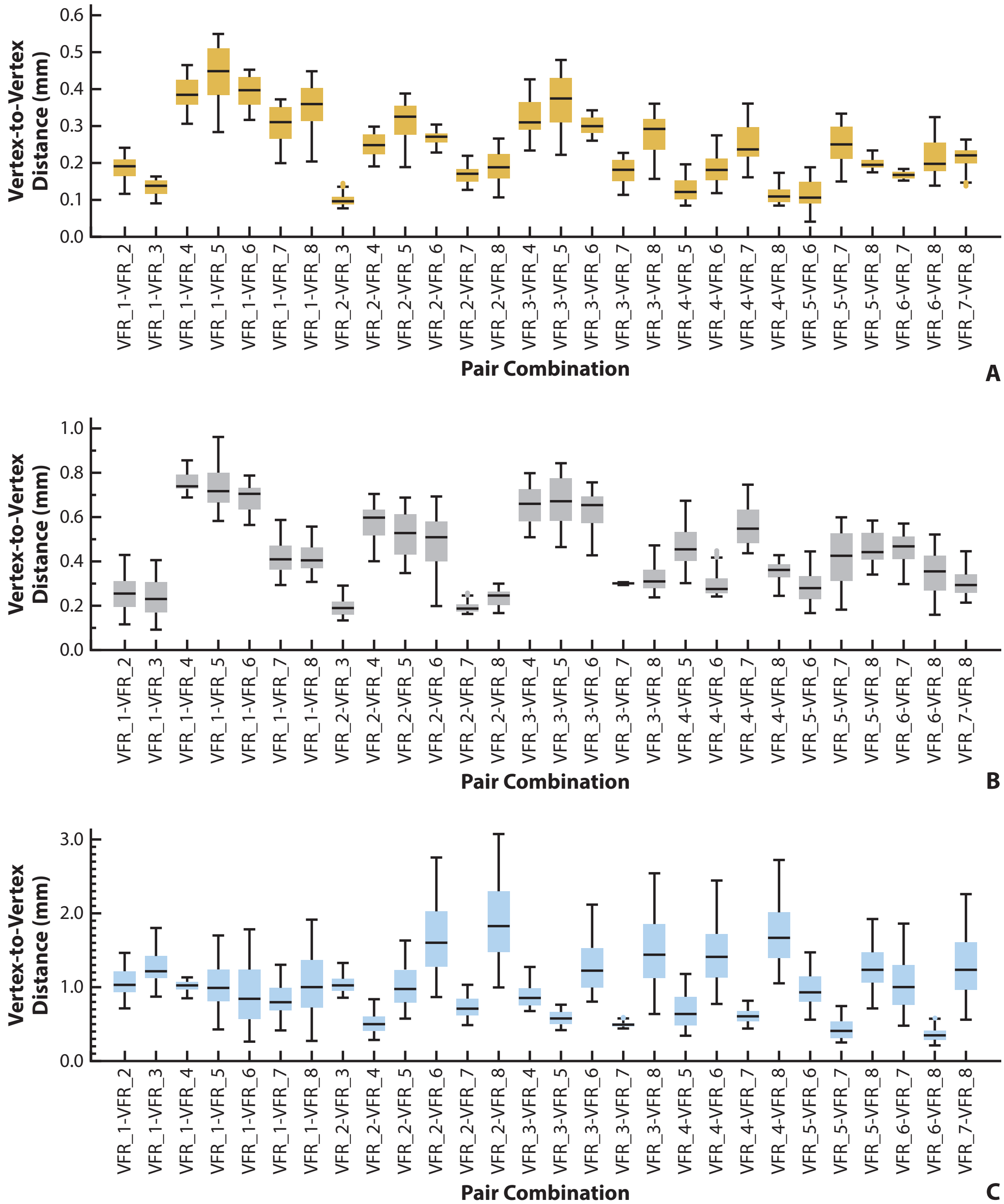

Figure 8. Box plots of vertex-to-vertex distances obtained in each distance map within each group. A, PHS group. B, 3DSC-T group. C, 3DSC-S group.

repeatability of the VF record technique and that its repeatability was greater with more accurate facial scanning methods. This is because, according to previous studies regarding the accuracy of facial scanning methods, PHS-type facial scanning methods are more accurate than 3DSC-T- and 3DSC-S-type methods.[21] The authors are unaware of a previous study comparing the accuracy of 3DSC-T- and 3DSC-S-type facial scanning methods, but the results of the present study suggest that 3DSC-T-type methods are more accurate than 3DSC-S-type methods. However, further studies are needed to verify this.

According to ISO standard 5725-1, the repeatability of a VF record technique can be defined as the extreme of its precision describing the minimum variability of the locations of maxillary digital scans with respect to the 3D face scans it provides.[19] Therefore, and considering that for this study VF records of a completely dentate adult with class I occlusion and mesoprosopic facial form were made by an experienced operator in a research

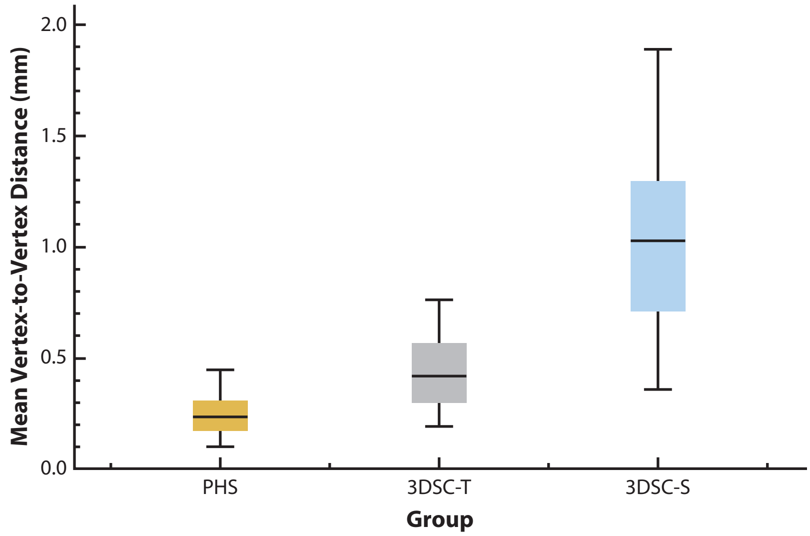

Figure 9. Box plot of mean vertex-to-vertex distances of distance maps obtained in each group.

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

		95% CI	
Group	Mean ±SD (Repeatability)	Lower Bound	Upper Bound
PHS	0.243 ±0.094	0.206	0.279
3DSC-T	0.437 ±0.171	0.371	0.504
3DSC-S	1.023 ±0.399	0.868	1.178

CI, confidence interval; SD, standard deviation.

Table 2. Results of between-group comparisons of mean vertex-to-vertex distances with Games-Howell post hoc test

Groups	*P*	Cohen d
PHS - 3DSC-T	<.001	1.413
3DSC-T - 3DSC-S	<.001	1.908
PHS - 3DSC-S	<.001	2.692

laboratory, it is to be expected that the ability of the VF record technique with PHS, 3DSC-T, and 3DSC-S facial scanning methods to provide repeatable locations of a maxillary digital scan with respect to a 3D face scan would be worse in clinical practice.

Although the repeatability of the VF record technique was found to be greater with the PHS facial scanning method than with the 3DSC-T and 3DSC-S facial scanning methods, the 3DSC-T and 3DSC-S methods present several advantages over the PHS method. These advantages include being less expensive and easier to use, thus lowering the barrier of entry for dental clinics to obtain 3D face scans, not requiring the projection of a visible light pattern on the patient's face and therefore not disturbing the patient, and requiring half the scanning time, thereby reducing the need for patient compliance.[26-28] Therefore, further studies are needed to improve the repeatability of the VF record technique with 3DSC-T and 3DSC-S facial scanning methods.

Limitations of this study included not being able to assess the trueness of the VF record technique. This was because the real location of a maxillary digital scan with respect to a 3D face scan is unknown in an in vivo study. In a previous study,[17] this location was estimated by aligning the maxillary digital scan first to a 3D digital replica of the craniofacial hard tissues and then to a 3D face scan, but this location can be affected by various errors. Further studies are needed to determine a methodology to assess the trueness of a VF record technique in an in vivo study.

CONCLUSIONS

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

1. The facial scanning method had a great impact on the repeatability of the VF record technique.
2. The repeatability of the VF record technique was statistically significantly greater with the PHS facial scanning method than with the 3DSC-T and 3DSC-S facial scanning methods and with the 3DSC-T facial scanning method than with the 3DSC-S facial scanning method, indicating that the VF record technique was more repeatable with more accurate facial scanning methods.

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

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