RESEARCH AND EDUCATION

Analysis of the influence of the facial scanning method on the transfer accuracy of a maxillary digital scan to a 3-dimensional face scan for a virtual facebow technique: An in vitro study

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ABSTRACT

Statement of problem. With the emergence of virtual articulators, virtual facebow techniques have been developed for mounting maxillary digital scans to virtual articulators. Different scanning methods can be used to obtain 3D face scans, but the influence that these methods have on the accuracy with which a maxillary digital scan is transferred to a 3D face scan is unknown.

Purpose. The purpose of this in vitro study was to analyze the influence of the facial scanning method on the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a virtual facebow technique.

Material and methods. Following a virtual facebow technique, a maxillary digital scan was transferred to a standard virtual patient –who had the maxillary digital scan in its real location– guided by an intraoral transfer element using different 3D face scans with the intraoral transfer element in place (reference 3D face scans) obtained with 2 different scanning methods: 10 obtained with an accurate scanning method based on structured white light technology and 10 obtained with a less accurate scanning method based on structure-from-motion technology. For each situation, deviation between the maxillary digital scan at the location obtained following the virtual facebow technique and at its real location was obtained in terms of distance using a novel methodology. From these distances, the accuracy was assessed in terms of trueness and precision, according to the International Organization for Standardization (ISO) 5725-1. The Student *t* test with Welch correction was used to determine if the accuracy with which the maxillary digital scan was transferred to the standard virtual patient was influenced by the facial scanning method used to obtain the reference 3D face scans (α=.05).

Results. Significant differences (P<.05) were found among the trueness values obtained when using the different facial scanning methods, with a very large effect size. A trueness of 0.138 mm and a precision of 0.022 mm were obtained using the structured white light scanning method and a trueness of 0.416 mm and a precision of 0.095 mm were acquired when using the structure-from-motion scanning method.

Conclusions. The accuracy with which a maxillary digital scan is located with respect to a 3D face scan in a virtual facebow technique is strongly influenced by the facial scanning method used.

CLINICAL IMPLICATIONS

Some virtual facebow techniques consist firstly of transferring a maxillary digital scan to a 3D face scan and then to a virtual articulator, enabling the creation of a virtual patient. For a virtual facebow technique to be accurate, and also to obtain an accurate virtual patient via the technique, it is important that the maxillary digital scan is transferred accurately to a 3D face scan. Given the wide variety of facial scanning methods available, it was demonstrated in the present study that the accuracy of the facial scanning method greatly influences the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a virtual facebow technique. Clinicians need to be aware of this when selecting the facial scanning method.

INTRODUCTION

A facebow[1] is used with a mechanical articulator to transfer functional and esthetic components from the patient to the articulator; specifically, the 3-dimensional (3D) location of the maxillary arch in relation to the cranial base and the mandibular transverse horizontal axis.[2] However, advances in digital dentistry[3] have resulted in mechanical articulators being replaced and/or supplemented by virtual articulators in dental computer-aided design-computer-aided manufacturing (CAD-CAM) systems.[4] In this virtual dental space, indirect digital scans of gypsum casts obtained with desktop scanners or direct digital scans of dental arches obtained with intraoral scanners are mounted on virtual articulators. For mounting indirect digital scans, an indirect digital workflow that incorporates analog steps is used.[4,5] In contrast, a fully digital workflow called direct digital workflow is used for mounting direct digital scans.[5,6] This workflow is comparable to the analog one, but it only uses digital data. Therefore, in the direct digital workflow facebows are replaced by alternative digital techniques called virtual facebow techniques (VFTs).[6-12]

Among the different VFTs those that consist of transferring a maxillary digital scan first to a 3D face scan and then to a virtual articulator have become popular,[10-12] since they also enable a virtual patient to be obtained. To transfer a maxillary digital scan to a 3D face scan VFTs use an intraoral transfer element (IOTE) also called a facebow fork. Once a maxillary digital scan is transferred to a 3D face scan, the virtual patient can be completed, as necessary, with a mandibular digital scan,[10-12] with additional 3D face scans,[13,14] or with 3D digital replicas of the craniofacial hard tissues.[14] The virtual patient is useful as it allows simulation of the treatment plan, exploration of patient expectations, and provides for effective communication among the patient, clinician, and dental laboratory technician.[15]

For VFTs to be accurate, and also to ensure an accurate virtual patient, it is important to transfer a maxillary digital scan to a 3D face scan accurately. However, analysis of the accuracy with which a maxillary digital scan is transferred to a 3D face scan for VFTs is lacking. This accuracy may be influenced by the accuracy of the digital scans used. Therefore, the accuracy of the intraoral scanner[16,17] or the facial scanning method[18-26] may influence the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT.

This in vitro study analyzed the influence that the facial scanning method has on the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT. The transfer accuracy obtained using 2 different facial scanning methods was compared. The first one was the single-camera photogrammetry method based on the structure-from-motion (SFM) photogrammetric scanning technology (SFM method). This method was used in the VFT presented by Solaberrieta et al,[10] and was selected because it is one of the least accurate, but at the same time least expensive, facial scanning methods. The second one was a hand-held optical scanner (Go!SCAN 20 scanner with VX element 6.3 SR1 software; Creaform, Inc) that uses a stereo camera arrangement working on structured white light (SWL) scanning technology (SWL method). This method was selected because with an accuracy of up to 0.1 mm is one of the most accurate methods for obtaining face scans. The null hypothesis was that the facial scanning method has no influence on the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT.

MATERIAL AND METHODS

The most popular VFTs consist of transferring the maxillary digital scan firstly, guided by an IOTE, to a 3D face scan with the IOTE in place (reference 3D face scan), then to an IOTE-free face scan in a predetermined head position and facial expression, and finally to a virtual articulator (Fig. 1).[10-12] Therefore, in this in vitro study the accuracy with which a maxillary digital scan was transferred to an IOTE-free 3D face scan was evaluated. To this end it was used a mannequin head (Phantom Head PK-2; Frasaco, GmbH) and an IOTE designed with a CAD software program (Solid Edge ST10; Siemens) and manufactured in a white-colored, non-toxic thermoplastic material (ABSplus-P430; Stratasys, Inc) with a 3D printer (Dimension Elite; Stratasys, Inc) that uses fused deposition modeling technology (Fig. 2).

The mannequin's maxillary arch (Fig. 3A) was scanned with an industrial reference scanner (ATOS Compact Scan 5M scanner with ATOS Professional V7.5 software; GOM, GmbH) that uses a stereo camera arrangement working on structured blue light scanning technology. As a result, a maxillary digital scan was obtained in the standard tessellation language (STL) file format (Fig. 3B). The digital scan was loaded into a reverse engineering (RE) software program (Geomagic Studio 2013; Geomagic, Inc) to remove the regions that did not correspond to the teeth and orient it with respect to a 20-mm edge cube, previously designed by using the CAD software program. This set was exported in the STL file format for subsequent use (Fig. 3C).

The IOTE was positioned in the mannequin's mouth by using a polyvinyl siloxane impression material (Aquasil Soft Putty Regular Set; Dentsply Sirona) (Fig. 4A). Then, without removing the IOTE from the mannequin's mouth, a facial scan was made with the reference scanner, and a reference 3D face scan was obtained in the STL file format (Fig. 4B). This facial scan was repeated 10 times under repeatability conditions[27] using the SWL and SFM scanning methods, resulting in 20 more reference 3D face scans in the tessellation with polygonal faces (OBJ) file format (Fig. 4C-D). Each facial scan with the SFM method consisted of making 27 digital photographs of the mannequin's face at different positions and angles using a digital single-lens reflex camera (PENTAX KS-1; Ricoh Imaging Co, Ltd) (camera settings: PENTAX-DA 35 mm f/2.4H lens, ISO 3200, aperture f/11.0, and a shutter speed of 1/40 second, with no flash). Then, to carry out the 3D reconstruction using the SFM technology, the photographs were loaded into a digital image processing and 3D data generation software program (Agisoft

Metashape Professional; Agisoft). To assist the software program in combining the photographs, a special pattern was projected onto the mannequin's face using a liquid-crystal display projector (ED-X12; Hitachi, Ltd). Also, since a non-metric camera was used, to obtain true-to-scale 3D face scans, a 30-cm ruler was placed under the mannequin's chin to provide a scale bar.

Once the reference 3D face scans were obtained, the IOTE was extracted from the mannequin's mouth. Then, the IOTE with the impression (Fig. 5A) was scanned with the reference scanner to obtain its digital scan in the STL file format (Fig. 5B).

A standard virtual patient with the maxillary digital scan in its real position was obtained in place of the IOTE-free 3D face scan. For that, the mannequin's face with the mouth completely open (Fig. 6A) was scanned with the reference scanner, capturing both the face and visible part of the maxillary arch. This resulted in an IOTE-free 3D face scan in the STL file format (Fig. 6B). Then, the IOTE-free 3D face scan and the maxillary digital scan were loaded into the RE software program and were aligned using the software program's implementation of the iterative closest point (ICP) algorithm (Fig. 7).

Each of the 21 reference 3D face scans were loaded separately into the RE software program in conjunction with the maxillary digital scan, the digital scan of the IOTE, and the standard virtual patient. Then, following the VFT the maxillary digital scan was first transferred to the reference 3D face scan guided by the digital scan of the IOTE and then to the standard virtual patient (Fig. 8). In this way, the relationship between 2 spatial locations of the maxillary digital scan was obtained: the real location (RL) and the one obtained through the VFT (OL). Both the maxillary digital scan at the RL and at the OL were exported in the STL file format. Therefore, 21 pairs of maxillary digital scans were obtained, which were divided into 3 groups based on the scanning method used to obtain the reference 3D face scan used to transfer the maxillary digital scan at the OL: the RS group, the SWL group, and the SFM group.

Afterwards, for each pair, the deviation of the maxillary digital scan at the OL from the maxillary digital scan at the RL was calculated. As maxillary digital scans are polygonal meshes, the deviation was expressed in terms of distances between the vertices of the 2 maxillary digital scans as a distance map. Moreover, since the aim was to measure the distance between 2 different spatial locations of the same maxillary digital scan, the distances between corresponding vertices were calculated. For this purpose, each of the 21 pairs of maxillary digital scans were loaded separately into a 3D data measurement software program (GOM Inspect 2019; GOM, GmbH). There, using the cube attached to the maxillary digital scan, an absolute coordinate system $(O_1XYZ)_1$ was created in the maxillary digital scan at the RL and another coordinate system $(O_2UVW)_2$ was created in the maxillary digital scan at the OL (Fig. 9). Once both reference systems were defined, the components d_x, d_y, and d_z of the vector **d** linking the origin of the coordinate system $(O_1XYZ)_1$ with the origin of the coordinate system $(O_2UVW)_2$ were obtained and the value of the cosines c(i, j) (i = U, V, W and j = X, W, Z) of the angles that the U, V, and W axes of the coordinate system $(O_2UVW)_2$ formed with each of the X, Y, and Z axes of the coordinate system $(O_1XYZ)_1$ were calculated. These values were used to define the homogeneous transformation matrix. This matrix can be interpreted as a mathematical operator capable of expressing, through the following system of matrix equations, both the translation and rotation to which each of the vertices of the maxillary digital scan at the RL must be subjected to reach its corresponding position in the maxillary digital scan at the OL:

$$\begin{Bmatrix} \boldsymbol{r}' \\ - \\ 1 \end{Bmatrix} = \begin{bmatrix} c(U,X) & c(V,X) & c(W,X) & d_x \\ c(U,Y) & c(V,Y) & c(W,Y) & d_y \\ c(U,Z) & c(V,Z) & c(W,Z) & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \boldsymbol{r} \\ - \\ 1 \end{Bmatrix}$$

, where **r** and **r'** are 2 position vectors representing, respectively, the position of the same generic vertex P of the maxillary digital scan at the RL and at the OL with respect to the coordinate system $(O_1XYZ)_1$ (Fig. 9). After calculating the 21 matrices, the geometry of the maxillary digital scans at the RL without the cube were exported in the American standard code for information interchange (ASCII) file format.

The 21 ASCII files were loaded separately into a spreadsheet software program (Microsoft Excel; Microsoft Corp). There, the system of matrix equations was applied to each of the **r** position vectors of the vertices to obtain the **r'** position vector of their corresponding vertices at the OL. The Euclidean d_P distances between the corresponding vertices (Fig. 9) were then calculated. As a result, 21 distance maps were obtained, each comprising 189 959 distances.

The distance data were loaded into a statistical software program (IBM SPSS Statistics, v26; IBM Corp) (Fig. 10). The accuracy with which the maxillary digital scan was transferred to the standard virtual patient using the SWL and SFM scanning methods to obtain the reference 3D face scan was assessed. For this purpose, the arithmetic mean value of each distance map was calculated (Table 1). The accuracy was assessed in terms of trueness and precision according to International Organization for Standardization (ISO) 5725-1.[27] Accordingly, trueness was considered as the ability of the VFT to provide locations of the maxillary digital scan (OLs) as close to its RL as possible and precision as the closeness of agreement between different locations of the maxillary digital scan acquired following the VFT (OLs) under the same conditions. After verifying the compliance of the normality assumption via the Shapiro–Wilk test for the distance data of each of the 2 groups (α=.05), for each group trueness was defined as the arithmetic mean of the mean distances and precision as the standard deviation of the mean distances (Table 1). Finally, to contrast the null hypothesis, taking into account that a quantitative variable (mean distances) and a 2-level categorical variable (SWL and SFM groups) were available, as the assumption of normality for each group was verified, Student *t* test hypothesis contrast for independent samples was used (α=.05). However, because of the non-compliance of the assumption of homogeneity of variances according to Levene test (α=.05), a modification of the degrees of freedom of Student *t* distribution was introduced to conduct the significance test (Welch correction).

RESULTS

Better trueness and precision values were obtained for the SWL group than for the SFM group (Table 1). This indicated that the maxillary digital scan was transferred more accurately to the standard virtual patient using the reference 3D face scans obtained with the SWL scanning method than with the SFM scanning method. The significance test showed statistically significant differences between the means of both groups (trueness) with an associated bilateral critical level P<.05 and a 95% confidence interval (CI) from 0.209 mm to 0.346 mm. To calculate the size that this effect of changing the scanning method had on the accuracy with which the maxillary digital scan was transferred to the standard virtual patient, the effect size was calculated according to the Cohen d (α=.05), obtaining a value of 4.037 with a 95% CI from 1.877 to 6.197, which represented a very large effect.

The RL of the maxillary digital scan was not achieved using the reference scanner to acquire the reference 3D face scan (Fig. 10). However, as expected, the OL of the maxillary digital scan was more accurate, since the calculated distances were smaller (Fig. 10). Indeed, the calculated maximum distances were 0.182 mm for the RE group, 0.241 mm for the SWL group, and 0.739 mm for the SFM group: all below 1 mm.

DISCUSSION

The present in vitro study analyzed the influence of the facial scanning method on the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT. For this purpose, it compared the accuracy with which a maxillary digital scan was transferred to a standard virtual patient –who had the maxillary digital scan in its RL– guided by an IOTE using different reference 3D face scans obtained from 2 different scanning methods of varying accuracy: 10 obtained with the accurate SWL scanning method, and 10 with the less accurate SFM scanning method. To assess the accuracy, in each situation the deviation between the maxillary digital scan at the OL and at the RL was obtained in terms of distances using a novel methodology. Given that maxillary digital scans are polygonal meshes and that the intention was to determine the deviation between 2 different spatial locations of the same maxillary digital scan, following this novel methodology the distances between the corresponding vertices of the 2 maxillary digital scans were calculated. This way, the novel methodology used allowed calculating the real distances between 2 locations of the same maxillary digital scan. These distances could not be measured with automatic tools, since they are not able to guarantee the correspondence between vertices. From the calculated distances, the accuracy was assessed in terms of trueness and precision, according to the ISO 5725-1.[27]

Based on the results, the null hypothesis that the facial scanning method has no influence on the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT was rejected. Furthermore, the effect size indicated that the effect of changing the facial scanning method was very large. The present study showed, as expected, that when more accurate facial scanning methods are used, a maxillary digital scan is more accurately transferred to a 3D face scan in a VFT. It should be noted that using one of the less accurate but more economical scanning methods –the only specific equipment that it requires is a digital image processing and 3D data generation software program– a maximum distance less than 1 mm has been calculated. Further studies will be necessary to determine the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT using the different facial scanning methods available.

The results also demonstrated that despite using a reference scanner to obtain the reference 3D face scan, it was not possible to obtain the RL of the maxillary digital scan. This indicates that despite using accurate digital scans, the RL of a maxillary digital scan with respect to a 3D face scan cannot be obtained in the analyzed VFT, mostly due to errors associated with the different alignments required by a VFT to transfer a maxillary digital scan to a 3D face scan. Therefore, further studies will also be necessary to analyze if these alignment errors can be minimized by using, for example, different IOTEs[10-14] and/or different alternatives for the alignment of different 3D face scans.[13-14]

When interpreting the results, it must be taken into account that as this was an in vitro study, patient factors that may affect the results, such as movements during scanning, saliva flow, or facial hair, were not taken into account. It should also be considered that, to analyze only the influence of the facial scanning method on the accuracy with which a maxillary digital scan is transferred to a 3D face scan in a VFT, both the maxillary dental arch and the IOTE were scanned with a reference scanner and that the IOTE-free 3D face scan was replaced by a standard virtual patient. For all that, it is to be expected that in real circumstances the calculated deviations will be larger.

CONCLUSIONS

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

1. The accuracy with which a maxillary digital scan is transferred to a 3D face scan in a virtual facebow technique is strongly influenced by the facial scanning method used.

2. The subsequent alignments required by a virtual facebow technique introduce inaccuracies when transferring a maxillary digital scan to a 3D face scan that cannot be solved using accurate digital scans.

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TABLE

Table 1. Mean distances (mm) and corresponding trueness and precision values (mm)

Repetition	Group	
	SWL	SFM
1	0.135	0.600
2	0.128	0.384
3	0.182	0.469
4	0.144	0.432
5	0.122	0.453
6	0.159	0.308
7	0.101	0.415
8	0.135	0.474
9	0.131	0.356
10	0.144	0.265
Trueness (AM)	0.138	0.416
Precision (SD)	0.022	0.095

AM, arithmetic mean; SD, standard deviation; SWL, structured white light; SFM, structure from motion.

FIGURES

Figure 1. Schematic of analyzed VFT. VFT, virtual facebow technique.

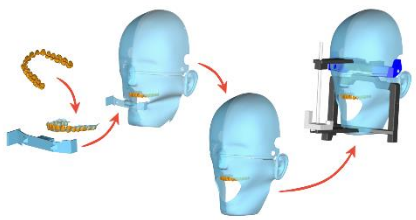


Figure 2. Ad hoc designed and additively manufactured IOTE. IOTE, intraoral transfer element.

Figure 3. Mannequin head's maxillary arch and its digital scan. A: Mannequin head's maxillary arch. B: Maxillary digital scan. C: Maxillary digital scan cleaned and aligned with cube.

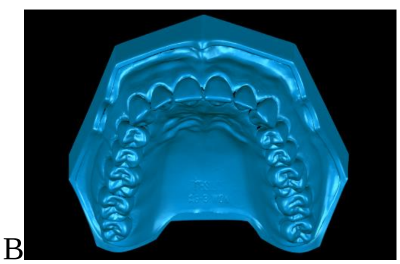
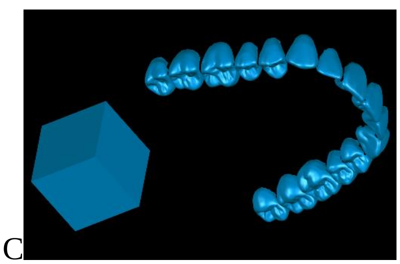
A  B  C 

Figure 4. Mannequin head with IOTE in place and its 3D face scans (reference 3D face scans) obtained with different scanning methods. A: Mannequin head with IOTE in place. B: Reference 3D face scan obtained with reference scanner. C: Reference 3D face scan obtained with SWL scanning method. D: Reference 3D face scan obtained with SFM scanning method. IOTE, intraoral transfer element. SFM, structure-from-motion. SWL, structured white light.

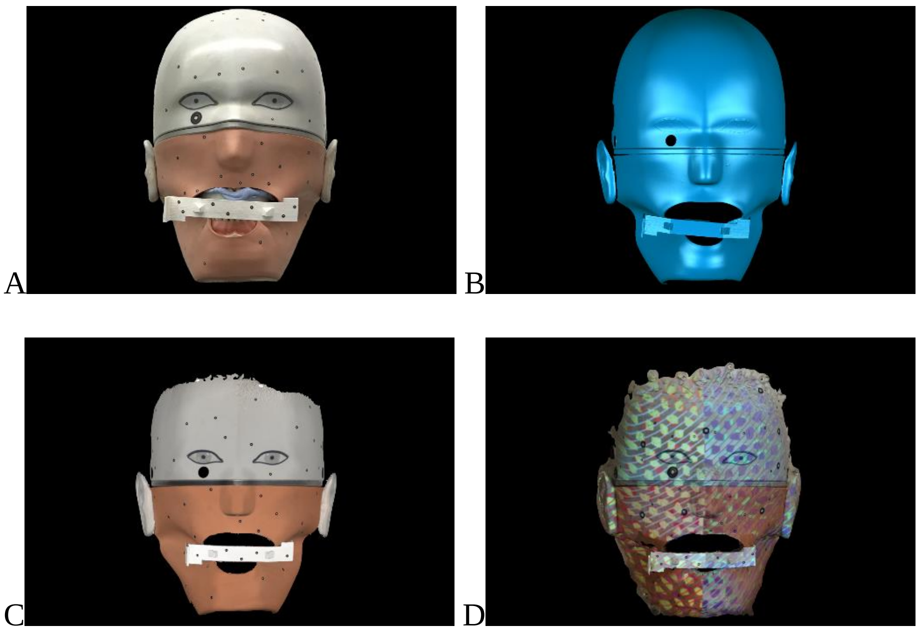


Figure 5. IOTE with impression and its digital scan. A: IOTE with impression. B: 3D digital scan of IOTE with impression. IOTE, intraoral transfer element.

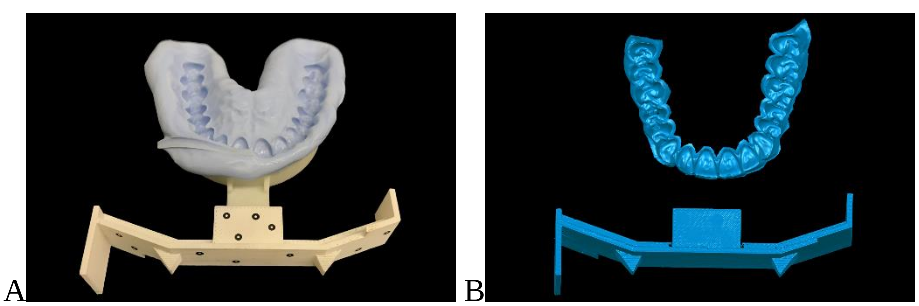


Figure 6. Mannequin head with its mouth completely open and its 3D face scan (IOTE-free 3D face scan). A: Mannequin head with its mouth completely open. B: IOTE-free 3D face scan. IOTE, intraoral transfer element.

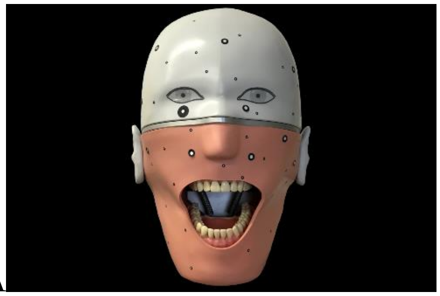
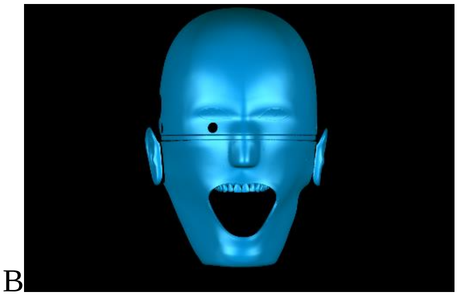
A  B 

Figure 7. Schematic of alignment process followed for obtaining standard virtual patient (red = regions selected for alignment using software program's implementation of ICP algorithm). ICP, iterative closest point.

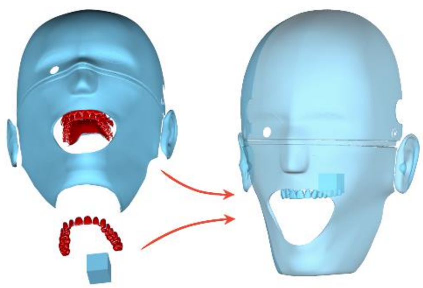


Figure 8. Schematic of alignment process followed for transferring maxillary digital scan to standard virtual patient (red = regions selected for alignment using software program's implementation of ICP algorithm). ICP, iterative closest point. IOTE, intraoral transfer element. OL, obtained location. RL, real location.

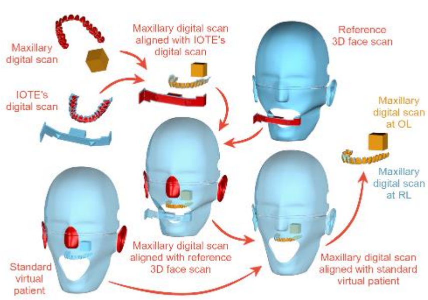


Figure 9. Schematic of calculation of distances between corresponding vertices. OL, obtained location. RL, real location.

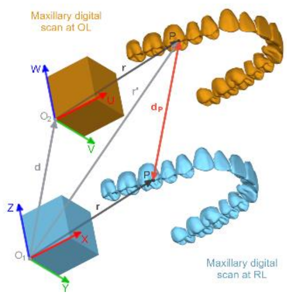


Figure 10. Box plot of distance data distribution. RS, reference scanner. SFM, structure-from-motion. SWL, structured white light.