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Trueness and Precision of Economical Smartphone-Based Virtual Facebow Records

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Abstract

Purpose: To investigate the trueness and precision of virtual facebow records using a smartphone as a three-dimensional (3D) face scanner.
Material and Methods: Twenty repeated virtual facebow records were performed on two subjects using a smartphone as a 3D face scanner. For each subject, a virtual facebow was attached to his/her maxillary arch, and face scans were performed using a smartphone with a 3D scan application. The subject's maxillary arch intraoral scan was aligned to the face scan by the virtual facebow fork. This procedure was repeated 10 times for each subject. To investigate if the maxillary scan is located at the right position to the face, these virtual facebow records were superimposed to a cone-beam computed tomography (CBCT) head scan from the same subject by matching the face scan to the 3D face reconstruction from CBCT images. The location of maxillary arch in virtual facebow records was compared with its position in CBCT. The "trueness" of the proposed procedure is defined as the deviation between maxilla arch position in virtual facebow records and the CBCT images. The "precision" is defined as the deviation between each virtual facebow record. The linear deviation at left central incisor (#9), left first molar (#14), and right first molar (#3), as well as angular deviation of occlusal plane were analyzed with descriptive statistics. Differences between two objects were also explored with Mann Whitney U test.
Results: The 20 virtual facebow records using the smartphone 3D scanner deviated from the CBCT measurements (trueness) by 1.14 ± 0.40 mm at #9, 1.20 ± 0.50 mm at #14, 1.12 ± 0.51 mm at the #3, and $1.48 \pm 0.56°$ in the occlusal plane. The VFTs deviated from each other by 1.06 ± 0.50 mm at #9, 1.09 ± 0.49 mm at #14, 1.11 ± 0.58 mm at #3, and $0.81 \pm 0.58°$ in the occlusal plane. When all sites combined, the trueness was 1.14 ± 0.40 mm, and the precision was 1.08 ± 0.52 mm. Out of eight measurements, three measurements were significantly different between subjects. Nevertheless, the mean difference was small.
Conclusions: Virtual facebow records made using smartphone-based face scan can capture the maxilla position with high trueness and precision. The deviation can be anticipated as around 1 mm in linear distance and 1° in angulation.

The virtual patient, a simulation created by superimposing varied three-dimensional (3D) images from an actual patient, is becoming a progressively popular toolset in the field of digital dentistry.[1,2] This revolutionary digital platform provides 3D volume renderings of the face, teeth, oral soft tissue, and even bony structures.[3,4] In this virtual clinical rendering, the information needed for dental diagnosis and prosthetic treatment planning can be easily obtained and integrated into the computer-aided design (CAD) and computer-aided manufacturing (CAM) workflows.[5–8]

One of the most crucial steps in the fabrication of a virtual patient includes pairing the maxillary cast alignment (angle and positioning) to the facial scan through the use of a virtual facebow technique.[9,10] This clinical protocol employs the use of a facebow fork, which contains both intraoral and extraoral references.[11] The intraoral component is often secured to the maxillary dentition using dental impression material, while the extraoral provides markers that orient the facebow fork with a facial scan. By superimposing the facial scan of the patient wearing the fork and the scan of the fork itself, the maxillary digital cast can be subsequently paired with the facial scan.[11,12]

As maxillary cast alignment is one of the first and most crucial steps within the digital workflow, its accuracy has influence over all subsequent steps including virtual articulator mounting, esthetic profile design, and location of the occlusal plane.[2,10,13,14] Lam et al described the repeatability (precision) of this procedure between the two techniques in a recent report.[12] The average deviation using calibrated stereophotogrammetry to mount the maxillary model was 0.86 ± 0.42 mm, while the deviation using an anatomic facebow was 3.66 ± 2.94 mm. Solaberrieta et al also assessed maxillary mounting deviation of an industrial scanner versus the conventional kinematic facebow and reported a mean maxillary cast mounting deviation of 0.75 ± 0.46 mm of their digital method.[15]

With the recent innovations in consumer technology, smartphone devices began to have the ability to scan a 3D object.[16] Compared to bulky and expensive industrial scanners and stereophotogrammetry devices, the smartphone offers a cost-effective and user-friendly alternative. A recent study reported that smartphone facial scans provided short scanning/data processing times and acceptable accuracy when compared with industrial scanners.[17] Nightingale et al investigated the reliability of using smartphone cameras and photogrammetry software to obtain face scans in 2020. They reported strong reliability even for inexperienced operators.[18] Thus, the use of smartphone scanners for face scans seems promising. However, there is no available study investigating if smartphone face scans are reliable for virtual facebow records. Therefore, the aim of this study was to investigate the trueness and precision of using 3D smartphone scans to locate maxillary 3D model on face scans. The primary goal is to observe the accuracy of smartphone-based virtual facebow transfer. The secondary goal is to explore if the results are stable between subjects and the null hypothesis is there is no accuracy difference between objects.

Materials and methods

The study was approved by the Institutional Review Boards of the University of Michigan (IRB# HUM00185470). The research design was adapted from studies of Ender et al and Muller et al.[19,20] Two healthy subjects (one male and one female, aged between 25 and 35) with full dentition (no missing teeth except for 3rd molars), free of facial abnormality, participated in the present study. An intraoral scanner (TRIOS Color Pod; 3Shape, Copenhagen, Denmark) was used to scan the subject's maxillary arch. The maxillary models were exported as Standard Tessellation Language (STL) format. The scans were imported into an open-source 3D computer software (Blender, version 2.80; The Blender Foundation, Amsterdam, Netherlands). Three reference points (mesh spheres with a diameter of 0.5 mm) were added on the mesial buccal cusps of the left (tooth #14) and right (tooth #3) maxillary first molar, and the mesial incisor angle of left maxillary central incisor (tooth #9) for future measurement.[21] The maxillary model, together with the reference points, was exported as an STL file for later use.

A smartphone (iPhone 11 Pro; Apple, Inc., Cupertino, CA) with a 3D scan application (Hege 3D scanner; from Apple App Store, developer: Marek Simonik) was used to obtain face scans in the present study (Fig 1A and B). The smartphone had a dot projector which could project 30,000 infrared dots on the subject while a built-in infrared camera (TrueDepth Camera; Apple, Inc., Cupertino, CA) could capture the images for 3D reconstruction.[17] The 3D scan application used could convert those images into a 3D model with a resolution range of 0.5 mm to 8.0 mm. Generated models could be subsequently exported in either STL (without color) or Polygon File (PLY) (with color) formats (Fig 1C).

A standardized protocol and scan mesh density of 0.5 mm was used to complete all facial scans. During face scanning, the subject was seated and told to refrain from motion. An operator held the phone by hand in front of the subject's face at approximately 20 cm (Fig 1B). The scan started at the midline of the face (level with the nasal tip) and firstly moved towards the left side to an extension of 45°, followed by scanning of the right side until an extension of 45° was reached. The face was then scanned downwards until an angle of 20° was reached, followed by a symmetrical motion upward to a maximal angle of 20°. The 3D models were subsequently exported as STL files.

To pair the maxillary scan with the face scan, virtual facebow records was made following the workflow described by Solaberrieta et al.[9] A poly(vinyl siloxane) occlusal registration material (Blu-Bite Fast Set Complete Package; Henry Schein, Inc., Melville, NY) was spread over a 3D printed facebow fork. Then the fork was placed into the subject's mouth and secured against the maxillary teeth. Facial scans were then repeated 10 times for each subject using the 3D printed facebow fork. The duration of each facial scan was recorded. Then, the facebow fork was removed and scanned using a desktop scanner (D2000; 3Shape, Copenhagen, Denmark). All scans were exported as STL files.

Scans of the face, facebow, and maxillary dentition were imported into a dental CAD software (Exocad version 2.2; exocad GmbH, Darmstadt, Germany). The following methods were employed to superimpose them: Firstly, taking the face scan as a fixed model, the scan of the facebow fork was aligned by its extraoral structure. Secondly, the maxillary scan was superimposed to the facebow fork by matching the impression part on the fork, which created a composite model including the face, facebow fork, and the maxillary arch scan (Fig 2). For each subject, 10 composite models were obtained, representing each virtual facebow record.

Cone beam computed tomography (CBCT) scans (3D Accuitomo 170; J Morita, Kyoto, Japan) images of the subjects were used as the reference. The setting for exposure was 5 mA and 90 kVp for 17.5 seconds. The field of view (FOV) was 170 mm × 100 mm, and the voxel size was set at 0.27 mm. CBCT images were imported into an implant planning software (Blue Sky Plan; Blue Sky Bio, LLC, Libertyville, IL), and a face soft tissue model was generated. Simultaneously, the

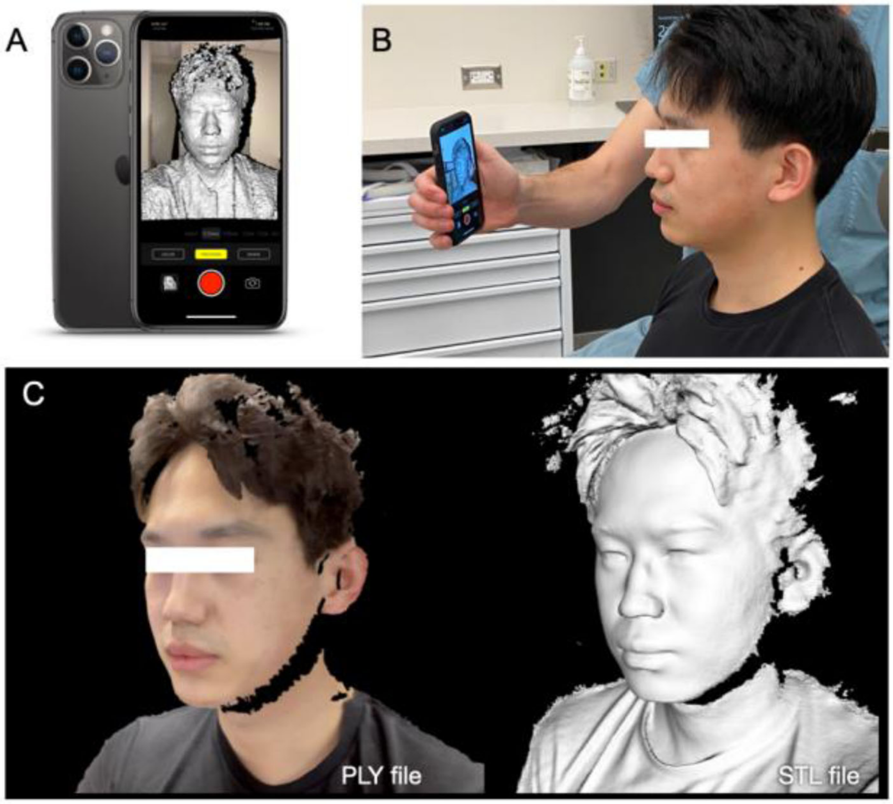

Figure 1 A, iPhone 11 pro with Heges application was used for face scan. B, Operator using iPhone to scan subject face. C, Face scan could be exported as PLY file (with color) or STL file (without color).

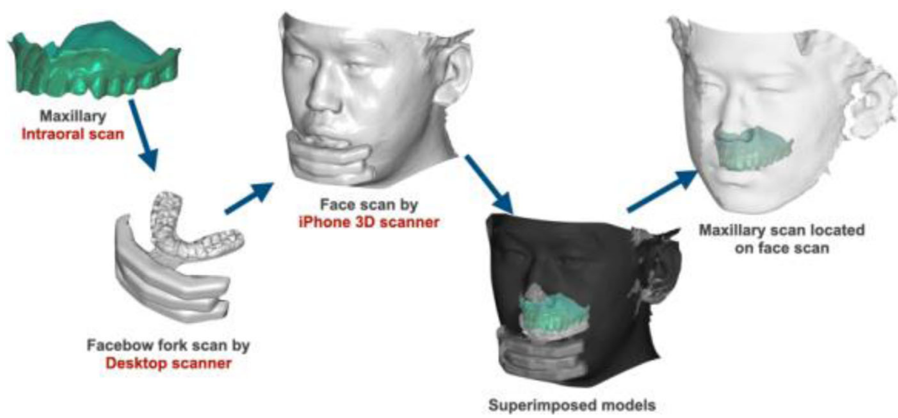

Figure 2 Virtual facebow transfer workflow.

maxillary scan was also imported into the implant planning software and superimposed to the teeth in CBCT. Together with the maxilla model, the face model from CBCT images was exported as an STL file. To compare the virtual facebow records with the CBCT, the model from CBCT was imported into Exocad. The composite models from the virtual facebow records were superimposed to the CBCT model by matching the face, using the best fitting algorithm (Fig 3).

The evaluation method of trueness and precision were adapted from Choi et al.[21] All the aligned models were imported into the open-source software, Blender. The x-, y-, z-coordinates of each reference point on #3, 9, and 14

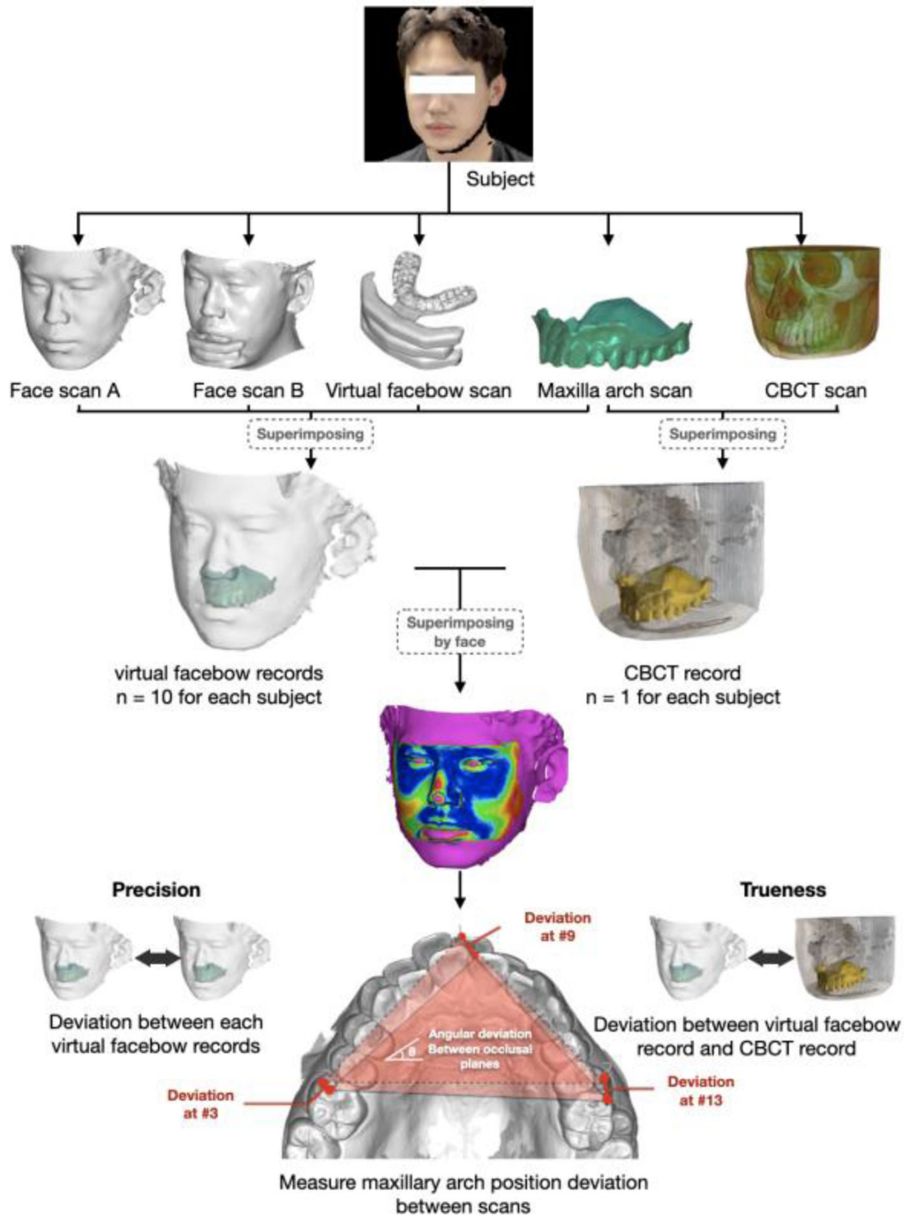

Figure 3 Experimental procedure.

teeth were obtained. The 3D linear distance between any two reference points could be computed with the following formula:

$$3D\ distance = \sqrt{(x1 - x2)^2 + (y1 - y2)^2 + (z1 - z2)^2}$$

The linear deviations between two models were measured as this 3D distance between the corresponding points. The angular deviation between the occlusal planes of each two models was also recorded.

Trueness was assessed as the mean deviation (linear and angular) between virtual facebow records and the CBCT record, while the precision was assessed as those between each two virtual facebow record.[19,20] All the measurements and calculation were performed automatically within Blender by using a Python (v3.8; Python Software Foundation, VA) script wrote by JL (Supplementary file 1). Thus, measurement errors from human observation were eliminated.

Statistical analysis was performed in a software (IBM SPSS Statistics v.20; IBM Corp., Chicago, IL). For the description of data, the number of observations, mean, standard deviation (SD), median, first quartile (Q1), third quartile (Q3), minimum (Min), and maximum (Max) were presented. To address if the workflow is consistent between different subjects, the trueness and precision of the two subjects were compared. Shapiro-Wilk test showed that the data was not normally distributed. Thus,

Table 1 Deviation between CBCT and virtual facebow record (Trueness)

Tooth location	Subject	Mean	SD	Q1	Median	Q3	Min	Max	$p^{\dagger}$
#9 Central Incisor (mm)	**A**	1.11	0.37	0.83	1.06	1.53	0.60	1.62	
	B	1.17	0.44	0.89	1.04	1.31	0.77	2.23	
	Both	1.14	0.40	0.88	1.04	1.43	0.60	2.23	0.912
#14 Left 1st molar (mm)	**A**	1.20	0.50	0.63	1.28	1.67	0.58	1.89	
	B	1.20	0.52	0.85	1.09	1.43	0.61	2.41	
	Both	1.20	0.50	0.83	1.10	1.59	0.58	2.41	0.853
#3 Right 1st molar (mm)	**A**	0.99	0.38	0.57	1.08	1.32	0.41	1.42	
	B	1.24	0.60	0.79	1.01	1.58	0.71	2.61	
	Both	1.12	0.51	0.77	1.01	1.36	0.41	2.61	0.684
All sites combined (mm)	**Both**	1.14	0.40	0.88	1.04	1.43	0.60	1.43	0.790
Occlusal plane (°)	**A**	1.90	0.52	1.67	1.86	2.26	0.83	2.72	
	B	1.06	0.20	0.93	1.02	1.23	0.72	1.42	
	Both	1.48	0.56	1.01	1.33	1.88	0.72	2.72	0.001*

Q1: first quartile. Q3, third quartile.

† Mann-Whitney U test comparing the difference between two subjects.

$^{*}p < 0.05$.

Table 2 Deviation between each virtual facebow record (Precision)

Tooth location	Subject	Mean	SD	Q1	Median	Q3	Min	Max	$p^{\dagger}$
#9 Central Incisor (mm)	**A**	1.12	0.53	0.69	1.21	1.39	0.14	2.44	
	B	1.00	0.46	0.67	0.90	1.28	0.33	2.16	
	Both	1.06	0.50	0.68	1.05	1.36	0.14	2.44	0.218
#14 Left 1st molar (mm)	**A**	1.11	0.48	0.80	1.02	1.43	0.17	2.08	
	B	1.08	0.50	0.67	0.97	1.35	0.41	2.29	
	Both	1.09	0.49	0.77	1.02	1.40	0.17	2.29	0.480
#3 Right 1st molar (mm)	**A**	1.24	0.60	0.74	1.19	1.59	0.30	2.68	
	B	0.96	0.53	0.55	0.83	1.20	0.23	2.19	
	Both	1.11	0.58	0.68	1.02	1.44	0.23	2.68	0.020*
All sites combined(mm)	**Both**	1.08	0.52	0.68	1.02	1.39	0.14	2.68	0.123
Occlusal plane (°)	**A**	0.94	0.58	0.52	0.80	1.51	0.15	2.18	
	B	0.67	0.55	0.29	0.41	0.79	0.11	1.94	
	Both	0.81	0.58	0.32	0.62	1.32	0.11	2.18	0.007*

Q1: first quartile. Q3, third quartile.

† Mann Whitney U test comparing the difference between two subjects.

$^{*}p < 0.05$

the Mann-Whitney U test was used to examine the data and the significance level was set as $\alpha = 0.05$.

Results

Twenty virtual facebow transfers were performed on two subjects. The mean face scan time was 33.25 ± 2.86 seconds.

The descriptive statistics of trueness of each subject are presented in Table 1. Combined trueness values are shown in Figure 4A. Overall, trueness of linear deviation at #9, 3, and 14 teeth were 1.14 ± 0.40 mm, 1.20 ± 0.50 mm, and 1.12 ± 0.51 mm, respectively. The average trueness of occlusal plane (angular deviation) was 1.48 ± 0.56°. There was no significant difference between the 2 subjects regarding the linear deviation. However, a significant angular trueness difference ($p < 0.001$) was found between subject A (1.90 ± 0.52°) and subject B (1.06 ± 0.20°).

Descriptive statistics of the precision of virtual facebow records are reported in Table 2 (data from each subject) and Figure 4B (data combined from both subjects). The mean linear deviation between each virtual facebow record was 1.06 ± 0.50 mm, 1.09 ± 0.49 mm, and 1.11 ± 0.58 mm at #9, 14, and 3, respectively. The angular deviation of the occlusal plane was 0.81 ± 0.58°. Significant differences between subjects A and B was found in the linear deviation at #3 (A: 1.25 ± 0.60 mm; B: 0.96 ± 0.53 mm; $p = 0.020$) and in the angular deviation (A: 0.94 ± 0.58°; B: 0.67 ± 0.55°; $p = 0.007$).

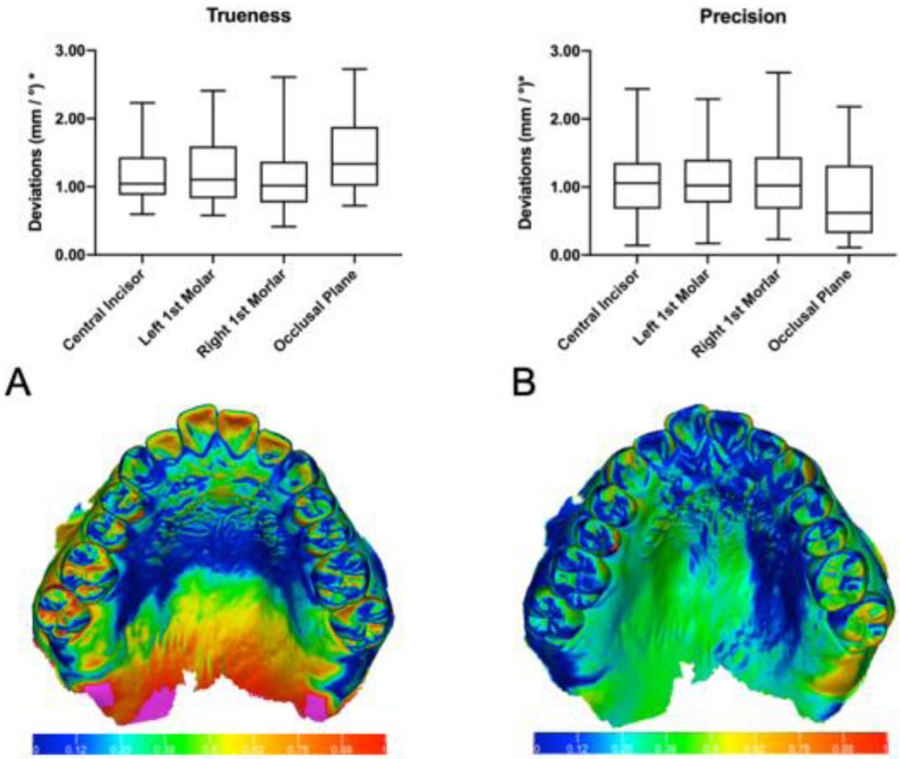

Figure 4 A, Boxplots and colormap of deviations (Trueness) between virtual facebow transfer and CBCT. B, Boxplots and colormap of deviations (Precision) between each virtual facebow transfer. *Deviations at incisor and molar sites were measured in millimeter (mm); deviations of occlusal plane were measured in degree (°).

Discussion

The present study investigated the trueness and precision of virtual facebow records using smartphone-based face scans. To the authors' knowledge, this is the first research studying the effectiveness of using a smartphone 3D scanner in virtual facebow transfer. Results showed that the maxillary position can be reproducibly recorded with an average trueness of 1.14 mm and precision of 1.09 mm. These data, combined with the short scanning time (33.25 ± 2.86 seconds), suggest that use of a smartphone 3D scanner in the dental clinic is promising. Also, significant differences in several measurement between the two subjects were found, which rejected the null hypothesis, suggesting there were be subject-dependent factors influencing the accuracy this workflow.

Several studies have reported the accuracy of facebow records using industrial scanners.[12,15,21] Choi et al studied the precision of a mechanical ear-bow record.[21] He reported mean deviations ranging from 1.5 to 6.7 mm at central incisor, left and right 1st molar.[21] Lam et al compared mechanical facebow transfer with virtual facebow record using stereophotogrammetry 3D face scan, finding a precision of 3.66 ± 2.94 mm in the conventional way and 0.86 ± 0.42 mm using a digital approach.[12] Taking the kinematic facebow transfer results as reference, Solaberrieta et al reported the trueness of virtual facebow record using an industrial scanner.[15] They found a mean deviation of 0.75 ± 0.46 mm between the virtual facebow records and the kinematic facebow transfer results. In this study, the average linear trueness from all sites was 1.14 mm, and the mean linear precision was 1.08 mm. Despite the differences in methodology, it appears that the virtual facebow records using smartphone 3D scanner technology produced a smaller deviation than analog facebow records in the literature. To this end, these pilot data suggest that further studies directly comparing smartphone 3D scanners with conventional methods and industrial 3D scanners are needed.

Between the subjects, a significant difference was presented in the angular trueness, angular precision, as well as linear precision at #14. These differences may come from the changed facebow fork fit on one of the subjects. If the facebow fork was not properly secured during face scanning, a larger deviation in the virtual facebow record would occur. Nevertheless, since these differences between the two subjects were small (0.84° difference in angular trueness, 0.27° difference in angular precision, and 0.28 mm difference in linear precision at right 1st molar), it may be lack of clinical significance.

In the present study, a novel facebow was designed for the use of smartphone scanner specifically. This was required because industrial 3D scanner has a higher resolution compared to a smartphone 3D scanner. Though the lower resolution from the smartphone scanner does not influence the

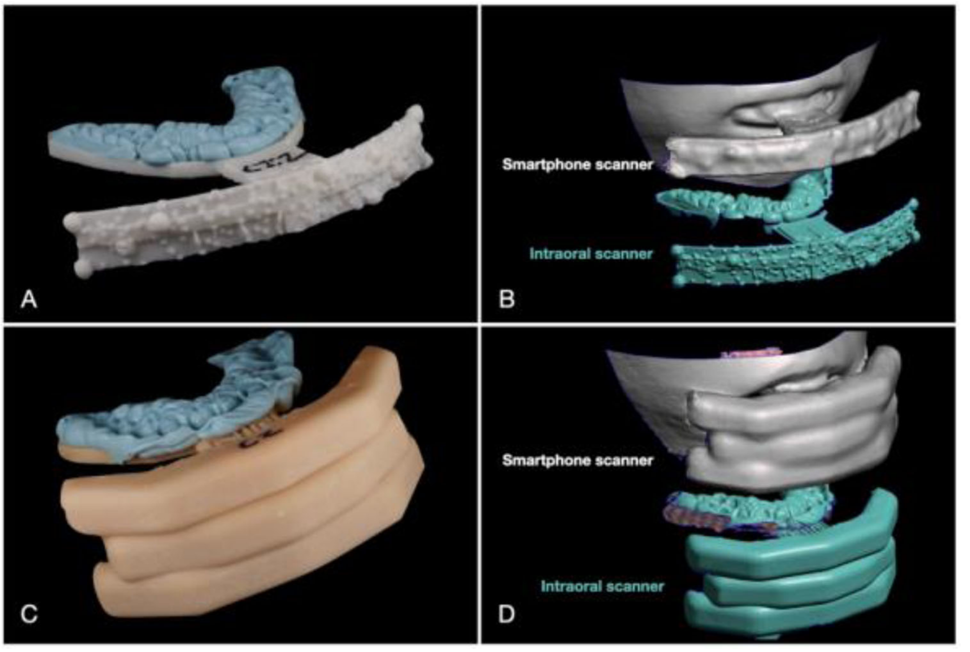

Figure 5 A, Virtual facebow fork with small optical markers. B, Smartphone scan of a virtual facebow fork with small optical marker was smoothed out, causing difficulty in registration. C, Virtual facebow fork with relatively smooth surface. D, Smartphone 3D scan of virtual facebow fork with relatively smooth surface was similar to scan from intraoral scanner.

dimensional accuracy of a large object,[17] voxel values that provide detail of an object are averaged in space, resulting in a smoothened/blended appearance (Fig 5A). When registering a lower resolution facebow fork scan (via smartphone 3D scanner) with a more detailed scan (by dental desktop scanner), this discrepancy leads to inaccuracies during the superimposition process (Fig 5B). To overcome this, a special virtual facebow fork was designed using Blender. It has a broad and smooth extraoral component designed specifically for digital pairing with a high-resolution partner (Fig 5C). Thus, the described novel facebow fork design prevents shape loss during smartphone 3D scanning, resulting in an acceptable superimposing during virtual facebow transfer (Fig 5D).

There are other 3D scanner applications for iPhone like Bellues3D Dental Pro (Bellus 3D Inc., Campbell, CA), ScandyPro (Scandy Co., New Orleans LA), and Qlone (EyeCue Vision Technologies LTD, Yokne'am Illit, Israel). The Heges was chosen for this research because only it produced a usable outcome for the VTF workflow in the pilot research. The Bellues3D Dental Pro, a face-scan application designed for dental use, produces good results when only the face is scanned. However, when it was used to scan a face with a facebow, the application usually trimmed the facebow away from the face, making the results very unstable for this workflow.

There are limitations to this study. First, only one smartphone (iPhone 11 pro) and 3D scanner application (Hege 3D scanner) were tested. Second, the factors influencing accuracy were not explored. Future studies should investigate the impact of different smartphones and 3D scanner applications on the accuracy of virtual facebow transfer as well as directly compare smartphones 3D scanners with conventional facebows and industrial scanners.

Conclusion

Virtual facebow records made using smartphone-based face scans can capture the maxilla position with high trueness and precision. The deviation can be anticipated as around 1 mm in linear distance and 1° in angulation.

Conflict of interest

The authors declare no conflicts of interest, either directly or indirectly, in the information or products listed in the paper.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplementary file 1