Integrating maxillary dentition and 3D facial photo using a modified CAD/CAM facebow

Peiqi Wang, Hui Xu, Rui Gu, Liwei Zhu, Ding Bai and Chaoran Xue*

Abstract

Background: Accurate integration of the dentitions with the face is essential in dental clinical practice. Here we introduce a noninvasive and efficient protocol to integrate the digitized maxillary dentition with the three-dimensional (3D) facial photo using a prefabricated modified computer-aided design/computer-aided manufacture (CAD/CAM) facebow.

Methods: To integrate the maxillary dentition with the 3D facial photo, the CAD/CAM facebow protocol was applied to 20 patients by taking a series of 3D facial photos in the clinic and integrating them in the laboratory. The integration accuracy of this protocol was compared with that of a valid 3D computed tomography (CT)-aided protocol concerning translational deviations of the landmarks representing maxillary incisors and maxillary first molars as well as the rotational deviation of the maxillary dentition. The intra- and inter-observer reproducibility was assessed, and the time of clinical operation and laboratory integration was recorded.

Results: This facebow-aided protocol generated 3D fused images with colored faces and high-resolution dentitions, and showed high reproducibility. Compared with the well-established CT-aided protocol, the translational deviations ranged from 0 to 1.196 mm, with mean values ranging from 0.134 to 0.444 mm, and a relatively high integration error was found in the vertical dimension (Z) with a mean ± standard deviation (SD) of 0.379 ± 0.282 mm. Meanwhile, the rotational deviations ranged from 0.020 to 0.930°, with mean values less than 1°, and the most evident deviation was seen in pitch rotation with a mean ± SD of 0.445 ± 0.262°. The workflow took 4.34 ± 0.19 min (mins) for clinical operation and 11.23 ± 0.29 min for laboratory integration.

Conclusion: The present radiation-free protocol with the modified CAD/CAM facebow provided accurate and reproducible transfer of the digitized maxillary dentition to the 3D facial photo with high efficiency.

Keywords: CAD/CAM, 3D stereophotogrammetry, Facebow

Background

Accurate measurement of the spatial relationship between the dentitions and the face is essential in clinical practice from both functional and esthetic perspectives [1]. The occlusal plane (OP) and the mandibular condyle need to be accurately recorded for precise occlusion evaluation, which may otherwise lead to a wrong diagnosis and even subsequent temporomandibular disorders [2]. For orthognathic patients, specifically, inaccurate evaluation of the maxillary arch position impairs the operative outcomes [3]. In addition to functional considerations, in the design and perception of facial esthetics, especially in the fields of orthodontics and prosthodontics, maxillary arch position relative to the facial soft tissue in six degrees of freedom, such as maxillary OP inclination, symmetry of the maxillary arch, and the anteroposterior position of maxillary incisors should be considered [4]. Virtual facebow transfer has been...
proposed to align the digital maxillary cast to the virtual articulator using standardized extraoral photographs [5]. However, traditional two-dimensional (2D) photos rely much on the head posture and photographing angle and only provide limited information. Therefore, three-dimensional (3D) facial photos with accurately integrated maxillary dentition are important in attempts to make accurate diagnoses and appropriate plans for dental treatment.

The reproduction of the static and dynamic jaw-skull relationship has long been aided by using an articulator, whereas it relies much on the operator experience and can be time-consuming [6], with debatable accuracy and reproducibility [7]. With advancements in technology, computed tomography (CT) scan has been proved to be helpful in the integration of 3D dentitions and 3D facial photos, providing high-resolution dental images and true-color skin texture with accurate tissue spatial relationships. With less chair-side time and a simpler procedure, CT scan constitutes an improved alternative to the articulator [8–14]. However, in cases of teenager maxillofacial deformity screening, in which the patients are young and thus prone to radiation injury; as well as fixed prosthesis, temporomandibular joint diseases, and orthodontic treatment, where the spatial relationship needs to be reproduced repeatedly during evaluation/diagnosis, treatment design, status record, and outcome evaluation, repeated dental CT scan is compromised by concerns of radiation exposure.

Therefore, non-invasive, easy, and efficient approaches have been developed using fully exposed anterior teeth on the 3D photo for integration [15–17]. To avoid errors and failures resulting from the unclear display of the anterior teeth, special facebow forks have been introduced to locate the maxillary dentition on the 3D face [18–21]. However, the efficiency and effectiveness of device manufacture, information acquisition, and data processing need further verification. This study aimed to establish a noninvasive and time-efficient protocol to transfer the maxillary dentition to the 3D facial photo using a prefabricated modified computer-aided design/computer-aided manufacture (CAD/CAM) facebow (Fig. 1, Step 1 and Step 2).

**Methods**

**Subject and criteria**

This study was performed from October 2017 to March 2018 at West China Hospital of Stomatolgy, Sichuan University, Chengdu, China. 20 consecutive surgical-orthodontic patients who required CT for diagnosis were enrolled to prevent excessive use of CT scans. The patients were listed for Le Fort I osteotomy or Le Fort I osteotomy plus bilateral sagittal split ramus osteotomy (BSSRO), of whom 7 were male patients (age range 19–35 years, mean age 26 years) and 13 were female patients (age range 18–34 years, mean age 24 years). Patients with a history of maxillofacial trauma or other congenital anomalies were excluded. Clinical data were collected before orthognathic surgery.

**Design and fabrication of the CAD/CAM facebow**

The CAD/CAM facebow was designed in Geomagic Freeform software (Geomagic, Morrisville, NC, USA). The facebow consisted of two parts: an intraoral part with an impression tray to acquire the dental impression and an extraoral part consisting of the tray handle and a reflection plate (Fig. 2). The extraoral part was specially designed for registration during the laboratory integration (Fig. 2B). To be specific, the impression tray was embossed with protrusions of different shapes on the upper surface of the handle and front end of the tray body for accurate and efficient surface registration (Fig. 2B, green). The reflection plate was composed of a central plane and a lateral plane with a 15° oblique angle in between on each side. Each of the lateral planes was engraved with a hemispherical protrusion (Fig. 2B, yellow). 3D geometries of the facebows in different sizes were exported in .obj files, and the facebows were 3D-printed (Lite600, Uniontech, Shanghai, China) and sterilized prior to use.

**Clinical data acquisition (Fig. 1, step 1)**

A facebow of a proper size was selected for each patient. The 3dMDface stereophotogrammetry system (3dMD, Atlanta, USA) was utilized to capture three 3D facial photographs, namely PHOTO1 of the patient with teeth in centric occlusion and soft tissue relaxed, PHOTO2 of the patient in a full smile, and PHOTO3 of the patient with the facebow in place and soft tissue relaxed (Fig. 1, Step 1). Before the capture of PHOTO3, the preliminary putty impression of the two-step putty/wash impression technique had been prepared. After being filled with impression material (Express™ VPS Impression Material, 3 M ESPE; St Paul, MN, USA), the final tray was placed into the patient’s mouth, and PHOTO3 was captured. All 3D photos were exported in .obj files. Chair-side time was recorded. Additionally, the digitized dental casts of each patient were obtained by an intraoral dental scanner (3Shape TRIOS; 3Shape, Copenhagen, Denmark), and the landmarks (UI, A6, B6) on each digitized dentition were selected (definitions seen in Table 1).

**Laboratory process of integration (Fig. 1, Step 2)**

**Establishment of the facial global reference system**

With the origin set on the soft tissue nasion point, a facial global reference system was constructed on PHOTO1/
Fig. 1 CAD/CAM facebow-guided protocol for integration of the maxillary dentition to the 3D facial photo. Step 1 (upper): clinical data acquisition. Step 2 (lower): laboratory integration. A Construction of a facial global reference system on PHOTO1. B–E Registration of B PHOTO3 to PHOTO1 by selecting the facial forehead areas (circled with the blue line), C the original facebow geometry to PHOTO3 by selecting the anterior surface of the reflection plate (circled with the yellow line), D the scanned facebow with impression to the original facebow geometry by selecting the upper surface of the handle and front end of the tray body (circled with the green line), and E the digitized maxillary dentition to the scanned facebow with impression by selecting the maxillary dentition (circled with the red line).

Fig. 2 Structure of the CAD/CAM facebow. A The intraoral structure: the impression tray for dental impression (marked red). B The extraoral structure: the specially designed front end of the tray body and tray handle (marked green) and the reflection plate (marked yellow) for laboratory integration.
PHOTO2 (Fig. 1, Step 2, A, Table 1) using Geomagic Studio 2013 (version 2013; Geomagic, Morrisville, NC, USA).

Registration of maxillary dentition to the 3D face
Facebow with the maxillary impression was scanned (3Shape D2000, 3Shape, Copenhagen, Denmark) and exported in .obj file. PHOTO1/PHOTO2 with the facial global reference system was set as a reference, and the Surface Registration approach in Geomagic Studio 2013 was utilized during the whole process of registration. There were four registration steps in total: (1) Registration of the 3D faces (Fig. 1, Step 2, B): PHOTO3 was registered to PHOTO1/PHOTO2 by selecting the forehead area. (2) Registration of the facebow (Fig. 1, Step 2, C): the 3D geometry of the original facebow was registered to PHOTO3 by selecting the anterior surface of the reflection plate. (3) Registration of the impression (Fig. 1, Step 2, D): the scanned facebow with impression was registered to the 3D geometry of the original facebow by selecting the upper surface of the handle and front end of the tray body. (4) Registration of the digitized dentition (Fig. 1, Step 2, E): the digitized maxillary dentition was registered to the scanned facebow with the impression by selecting the maxillary dentition.

In this way, the maxillary dentition was registered to PHOTO1 in the facial global reference system. Laboratory time of the proposed process was recorded.

Assessment of reproducibility and accuracy
Assessment of accuracy
The accuracy of the CT-based integration has been well-documented [22], and the CT-aided integration was utilized as the reference standard for accuracy assessment. With data from the spiral CT captured with teeth in centric occlusion and soft tissue relaxed (Philips MX16 EVO CT scanner), 3D reconstruction of the skull with both hard and soft tissues was performed using Mimics (version 10.01; Materialise, Leuven, Belgium).
This reconstructed 3D skull played a similar role to the CAD/CAM facebow in the following procedure. It was registered to PHOTO1/PHOTO2 with the facial reference system using the Surface Registration approach in Geomagic Studio 2013 by selecting the forehead area of the soft tissue, and thus the spatial relationship between soft and hard tissues was accurately recorded. Digitized dental casts with landmarks were then superimposed on the hard tissue of the registered 3D skull. Thus, the maxillary dentition integrated by the CT approach was registered to PHOTO1/PHOTO2 in the facial global reference system.

The coordinate values (X, Y, Z) of three landmarks (UI, A6, B6) on the maxillary dentition in the CT-integrated position were recorded, and the orientations (pitch, roll, yaw) of the maxillary dentition were all set as 0° (Fig. 3A). Afterward, the CT-integrated maxillary dentition with the landmarks was registered to the position of the facebow-integrated dentition (Fig. 3B, C). The coordinate values of the landmarks in the position of the CAD/CAM facebow-integrated dentition (green) were recorded. The rotational deviations between the CT-integrated and facebow-integrated dentitions and the translational deviations as represented by differences between the coordinates of the landmarks in the CT-integrated dentition (blue) and the facebow-integrated dentition (green) were automatically recorded.

Assessment of accuracy

A 3D skull reconstructed from CT data was registered to PHOTO1 with the facial global reference system. The coordinate values of the pre-selected landmarks (blue) on the maxillary dentition were recorded in the CT-integrated position (grey), and the orientations (pitch, roll, yaw) of the maxillary dentition were all set as 0°. By selecting the same region on the dentition, the CT-integrated dentition (grey) with the landmarks “glued” on it was registered to the CAD/CAM facebow-integrated dentition (red). The coordinate values of the landmarks in the position of the CAD/CAM facebow-integrated dentition (green) were recorded. The rotational deviations between the CT-integrated and facebow-integrated dentitions and the translational deviations as represented by differences between the coordinates of the landmarks in the CT-integrated dentition (blue) and the facebow-integrated dentition (green) were automatically recorded.

Assessment of intra- and inter-observer reproducibility

To analyze the intra- and inter-observer reproducibility of the CAD/CAM facebow-guided approach, two independent observers (A and B) performed the integration twice with a 2-week interval between the first and second ones. For these repeated integrations, 12 measurements including the coordinate values (X, Y, Z) of each landmark (UI, A6, B6) and orientations (pitch, roll, yaw) of the maxillary dentition (Table 1) were automatically recorded in the Geomagic Studio as mentioned above.

Statistical analysis

The observer intra- and inter-observer reproducibility was evaluated using intra-class correlation coefficient (ICC) and Bland-Altman plots. ICC > 0.75 represented excellent agreement beyond chance. Bland-Altman plots were established using the software of Medcalc.
Absolute values of all deviations were used for the assessment of accuracy. Mean translational deviations (X, Y, Z) of each landmark (UI, A6, B6) on the maxillary dentitions, and mean rotational deviations (pitch, roll, and yaw) of the maxillary dentitions between the CAD/CAM facebow approach and the valid CT approach were presented. Shapiro-Wilk test showed that some variables were not normally distributed. To compare the deviations above with a clinically acceptable error (1 mm in translation or 1° in orientation), paired t-test was applied for normally distributed variables while Wilcoxon matched-pair test was applied for non-normally distributed variables. A level of α = 0.05 was set for significance.

**Results**

**Reproducibility of the facebow-aided integration**

The integration procedure using the CAD/CAM facebow was feasible in all patients and showed high intra- and inter-observer reproducibility as suggested by the ICC values of both planar and rotational descriptors which were much higher than 0.90 (Table 2). Moreover, the Bland-Altman plots (Fig. 4) of the differences between measurements (between operators and time-interval) revealed low mean differences and 95% limits of agreement, indicating high reproducibility.

**Accuracy of the facebow-aided integration**

The accuracy of the CAD/CAM facebow-aided protocol was evaluated via absolute translational and rotational deviations from the 3D CT approach (Table 3). As for translational descriptors, the mean deviations of all landmarks were significantly lower than 1 mm (P < 0.01). Specifically, deviations in the vertical dimension (Z) were the most evident while those in the transversal direction (X) were the lowest, with means ± SDs of 0.379 ± 0.282 mm and 0.155 ± 0.118 mm, respectively. Among all the landmarks, vertical deviations of A6 and B6 ranged from 0.021 to 1.035 mm and 0.026 to 1.196 mm, respectively, higher than those of UI (ranging from 0.008 to 0.675 mm).

In respect of rotational deviations, the mean deviations in pitch, roll, and yaw were significantly lower than 1° (P < 0.01), with the means ± SDs of 0.445 ± 0.262°, 0.299 ± 0.199°, 0.287 ± 0.150°, respectively.

**Efficiency of the facebow-aided protocol in clinical operation and laboratory preparation**

For clinical data acquisition, the average duration was 4.34 ± 0.19 min (mins). The process of capturing and checking 3D facial photos (including positioning of the final tray to the patient’s mouth) took 1.32 ± 0.15 min, while making the initial tray with the preliminary putty impression and setting the impression material took 3.02 ± 0.15 min, taking up about 69.6% of the clinical
time. As for the laboratory integration, the average total time was 11.23 ± 0.29 min. It took 3.00 ± 0.11 min to scan the tray with impression and 8.23 ± 0.30 min to perform the successive registration. This protocol provided 3D fused images with colored faces and high-resolution dentitions with all data registered in the facial global reference system, 3D fused facial photographs with accurately positioned digitized dentitions could be generated, even for teeth with metal brackets (Fig. 5). To re-establish the “red and white esthetics”, teeth and gingiva on the digitized dental casts were colored the same as those on PHOTO2 (Fig. 5). Moreover, this integrating approach, together with techniques such as virtual tooth alignment, virtual prosthodontic planning, and surgery simulation, can provide relatively accurate visual 3D treatment prediction (Fig. 5C).

**Discussion**

This study introduced a CAD/CAM facebow to assist the transfer of maxillary dentition to the 3D facial photo with high accuracy and reproducibility in six degrees of freedom. With short-time clinical operation and reduced laboratory preparation, this radiation-free protocol has been proven simple, convenient, and time-efficient for routine clinical use. The approach may be more clinically meaningful since the original digital dentitions can be replaced with the predicted post-treatment digital dentition and

---

Table 2: Intra- and inter-observer reproducibility of the integration procedure using CAD/CAM facebow-guided protocol

| Measurement     | Intra-A | Intra-B | Inter-A and B |
|-----------------|---------|---------|---------------|
| **Translational deviation** |         |         |               |
| X               | 0.9998 (0.9994 to 0.9999) | 0.9992 (0.9980 to 0.9997) | 0.9991 (0.9978 to 0.9997) |
| Y               | 1.0000 (0.9999 to 1.0000) | 1.0000 (0.9999 to 1.0000) | 0.9999 (0.9998 to 1.0000) |
| **Rotational deviation** |         |         |               |
| Pitch           | 0.9976 (0.9940 to 0.9991) | 0.995 (0.9873 to 0.9980) | 0.9952 (0.9878 to 0.9981) |
| Roll            | 0.9977 (0.9942 to 0.9991) | 0.9880 (0.9721 to 0.9956) | 0.9861 (0.9652 to 0.9945) |
| Yaw             | 0.9977 (0.9941 to 0.9991) | 0.9967 (0.9917 to 0.9987) | 0.9935 (0.9837 to 0.9974) |

*Results are given as intra-class correlation coefficient (ICC) (95% confidence interval [CI]). Intra-A, intra-observer reproducibility for observer A; Intra-B, intra-observer reproducibility for observer B; Inter-A and B, inter-observer reproducibility between observer A and observer B. CAD/CAM, computer-aided design/computer-aided manufacturing.

Table 3: Translational deviations of the landmarks and rotational deviations of the maxillary dentition between CAD/CAM facebow and CT approaches

| Measurement | Mean   | SD     | Minimum | Maximum |
|-------------|--------|--------|---------|---------|
| **Translational deviation (mm)** |         |        |         |         |
| X           | 0.192  | 0.121  | 0.006   | 0.430   |
| Y           | 0.248  | 0.221  | 0.002   | 0.697   |
| Z           | 0.353  | 0.169  | 0.008   | 0.675   |
| **Rotational deviation (°)** |         |        |         |         |
| Pitch       | 0.445  | 0.262  | 0.040   | 0.930   |
| Roll        | 0.299  | 0.199  | 0.020   | 0.720   |
| Yaw         | 0.287  | 0.150  | 0.030   | 0.540   |

*Absolutes were given.

CAD/CAM: computer-aided design/computer-aided manufacturing; CT: computed tomography; SD: standard deviation.
Fig. 5 3D images in a full smile. 

A, B 3D facial photograph with original translucent dentition (upper) and 3D fused facial images with clear digitized dentition (lower). 

C 3D fused facial images with clear digitized dentition before treatment (upper) and 3D fused facial images with clear predicted digitized dentition (lower).
soft tissue can be simulated. The estimated results of the treatment can be visually presented to the patients and peers for communication [13, 14].

**Existing protocols to integrate the maxillary dentition and the 3D facial photo**

As 3D evaluation provides ample information compared with traditional standardized 2D photos, integration of maxillary dentition and 3D facial photos is important in the diagnosis, treatment, and follow-up evaluation of dental treatment. Integration procedures aided by CT scans have shown satisfactory accuracy [8, 9], but the use is limited due to the radiation exposure, especially in cases requiring repeated integration. In 2008, Rangel et al. proposed to integrate a digital dental cast into a 3D facial picture according to the exposed teeth on the photo [15], and the technique has been utilized and modified since then [16]. Because the anterior teeth were utilized as a reference, any slight deviation on the digital dental images would cause errors in the position of the whole dentition, especially in cases with saliva biofilm or metal brackets where the surfaces of teeth are hard to be recognized [16].

Therefore, integration techniques with transfer units gained extended applications as they dispensed with the matching of the tooth surfaces [18–21]. A transfer unit often comprised an intraoral part to acquire the dental impression and an extraoral structure for registration with the 3D face, and the modifications mainly lay in the design of the extraoral part. For instance, Bechtold et al. [24] introduced a transfer tray containing a facebow fork and a 125-mm-long rod with transmission balls. More recent studies have proposed extraoral components of smaller sizes [18, 20] and the integration has been facilitated with the aid of special targets on the facebow [19]. However, these protocols required full scans of the whole device and thus needed large-volume desktop scanners or long-time scanning with intraoral scanners.

**The special design of the present CAD/CAM facebow**

Compared with the CT-aided approach, this proposed procedure poses no radiation and costs less (Table 4), and therefore is more cost-effective and widely applicable. In comparison with the previous integration approaches using transfer units, the present CAD/CAM facebow was embedded with special designs for registration. In addition to the registration targets in the front (reflection plate), there were also patterns for registration on the upper surface of the handle and front end of the tray body (Fig. 2B). In this way, we only needed to scan the upper side of the handle on the scanned facebow to register it to the original facebow whose 3D geometry had been saved in advance (Fig. 1, Step 2, D, Fig. 2 A), thus simplifying and expediting the laboratory integration. Moreover, horizontal and vertical lines as well as the hemispheric protrusions were specially designed on the

### Table 4

|                      | CT approach       | CAD/CAM facebow approach | Traditional facebow approach |
|----------------------|-------------------|--------------------------|-----------------------------|
| **Radiation (µSv)**  | 30-1073*          | 0                        | 0                           |
| **Cost ($)**         | CT scan 70        | Facebow tray (with impression material) 30 | Facebow tray 15 |
|                      | 3D image acquisition 5 | 3D image acquisition 5 | Articulator mounting 85 |
| **Total**            | 75                | 35                       | 100                         |
| **Effectiveness**    | Soft tissue Yes   | Soft tissue Yes          | Soft tissue No              |
|                      | Bone Yes          | Bone No                  | Bone No                     |
|                      | Dentition Yes     | Dentition Yes            | Dentition Yes               |
|                      | Spatial relationship Yes | Spatial relationship Yes | Spatial relationship Yes |
| **Efficiency (min)** | CT scan 1.5–2.5   | 3D image acquisition 4–4.50 | Facebow application 10–15 |
|                      | Laboratory reconstruction 2–3 | Laboratory integration 11–11.5 | Laboratory mounting 40–60 |
| **Total**            | 3.5–5.5           | 15–16                    | 50–75                       |

* Radiation of CT approach is given as effective dose exposure by American Dental Association
** Cost of each approach represents the prices charged for each patient in West China Hospital of Stomatology, Sichuan University, Chengdu, China
*** Efficiency of each approach is given as approximate clinical and laboratory time spent by the same group of experienced operators. The duration of laboratory mounting included time for the plaster to cure. The CBCT scans were taken by 3D Accu-tomo (Morita, Japan), the spiral CT scans were taken by MX16 EVO (Philips, Holland), and the time spent on CT scans includes the procedure of patient and machine preparation.

**CT** computed tomography; **CAD/CAM** computer-aided design/computer-aided manufacturing
reflection plate to limit deviations in vertical dimension or roll orientation of the facebow during surface-based registration (Fig. 1, Step 2, C, Fig. 2B).

The protocol included clinical data acquisition and laboratory integration, average durations of which were 4.34 and 11.23 min, respectively. Specifically, the setting of the impression material took up about 69.6% of the clinical time. Therefore, the one-step impression can be adopted in place of the two-step impression in future practice to accelerate the procedure.

**Accuracy of the CAD/CAM facebow protocol as measured in six degrees of freedom**

Although some integration protocols have been suggested, only limited information has been given on their accuracy. Generally, similar to the present study, the accuracy has been represented by measuring the deviations between the virtual facebow-aided integration and the CT record. Lam et al. [18] presented the deviations measured in Euclidean distances: 0.66 mm, 0.58 mm, and 0.26 mm for the maxillary incisors, canines, and first molars, respectively. Further, Li et al. [20] reported the 3D deviations including Euclidean deviations of the landmarks and the rotational deviations of the occlusal plane. To be specific, the deviations of the maxillary incisor, the left first molar, and the right first molar were 1.14 mm, 1.20 mm, and 1.12 mm, respectively, and the mean rotation of the occlusal plane was 1.48°. However, since the dental assessment comprises positional measurements in six degrees of freedom [25], it would be more clinically reliable to specify the accuracy evaluation into measurements in the translational dimensions (transversal, sagittal, vertical translations) and rotational dimensions (pitch, roll, and yaw).

In the present study, the integration accuracy of the CAD/CAM facebow approach was determined using a semiautomatic 3D measuring procedure, incorporating measurements of the translational deviations of the landmarks and the rotational deviations of the maxillary dentition. Overall, the protocol showed satisfactory accuracy, with mean translational deviations ranging from 0.134 to 0.444 mm for all landmarks, and mean rotational deviations ranging from 0.299° to 0.445° for the maxillary dentitions. Interestingly, the vertical deviations were the most evident translational deviations for all landmarks and tended to be higher in the molar region (ranging from 0.021 to 1.196 mm) than in the incisors (ranging from 0.008 to 0.675 mm) (Table 3). Moreover, the pitch of the maxillary dentitions was relatively high compared with roll and yaw (Table 3). Presumably, the subtle errors during superimposition on the reflection plate in the vertical dimension may be magnified along the dentition since the surface registration was performed in the anterior region. However, the exact reason still needs to be explored to further strengthen the integration protocol.

**Sample selection of the present study**

In this study, surgical-orthodontic patients were enrolled for the following reasons: First, these patients required CT for diagnosis, and therefore, excessive CT scans could be avoided. Secondly, aberrances often existed in the position and/or orientation of the maxillary dentition among these patients, providing a better simulation of the clinical application scenarios of the procedure. Moreover, some of the patients wore metal brackets which made the tooth surface hard to recognize, and thus the integration protocol could be stringently tested and trained for higher accuracy.

**Limitations and future expectations of the present protocol**

Interestingly, although the reproducibility of the present protocol was high (Table 2; Fig. 4), the translational measurements showed relatively larger intra- and inter-observer biases than the rotational measurements. This could probably be due to the potential errors occurring in the extra step of identifying the landmarks. Therefore, procedures such as automatic landmark determination could be adopted to further strengthen the reproducibility and reliability of the measurement protocol.

It is also worth noting that one of the limitations is that the laboratory integration still took a relatively long time due to the successive registrations. Though clinically acceptable, the duration may be reduced by improving the relevant 3D software and technician/dentist proficiency. Moreover, with the multiple integration steps, the accuracy of the protocol relies much on the quality of 3D images and 3D models. The scanning systems (3Shape TRIOS intraoral scanner and 3dMDface system) utilized in the present study have been terrified to have high accuracy [26–28], but the potential of errors derived from the 3D image/model should be considered when applying protocol with other equipment or software.

Another concern may be focused on the cost of 3D stereophotogrammetry. The 3D faces in the present protocol were acquired with the 3dMD system which was fast and accurate, but bulky and expensive [26]. With more low-cost 3D cameras or relative smartphone applications emerging, this protocol would impose fewer economic burdens on hospitals or dental clinics. Moreover, incorporation of the relationship between the two jaws is needed to further strengthen the clinical application of this protocol.
Conclusion
The modified CAD/CAM facebow-aided protocol provided accurate and reproducible integration of the digitized maxillary dentition and the 3D facial photo with high clinical efficiency.

Abbreviations
OP: Occlusal plane; 2D: Two dimension, two dimensional; 3D: Three dimension, three dimensional; CT: Computed tomography; CAD/CAM: Computer-aided design/computer-aided manufacture; SD: Standard deviation.

Acknowledgements
Not applicable.

Author contributions
WPQ participated in the design of the study and the registration protocol, interpreted data, organized figures, and drafted the manuscript. XH participated in the design of the study and the registration protocol and contributed to manuscript revision. GR contributed to data analyses and interpretation. ZLW contributed to data analyses and participated in figure draft, and contributed to manuscript revision. All authors read and approved the final manuscript.

Funding
This study is financially supported by the Chinese Orthodontic Society, Chinese Stomatological Association (COS-C2021-02), the Project of Science and Technology Support Program of Sichuan Province, China (2014SZ0157), Interdisciplinary Innovation Project of West China Hospital of Stomatology, Sichuan University (BD-03-201108), and Clinical Research Project of West China Hospital of Stomatology, Sichuan University (LCYJ-2022-YY-3).

Availability of data and materials
All data generated or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations
Ethics approval and consent to participate
This research was performed in accordance with the Declaration of Helsinki and approved by the Ethics Committee of West China Hospital of Stomatolgy, Sichuan University (WCHSIRB-D-2016-003R1), and written informed consents were obtained from participants included in this paper.

Consent for publication
Written informed consent for publication was obtained.

Competing interests
The authors declare that they have no competing interests.

Received: 23 May 2022 Accepted: 16 August 2022 Published online: 26 August 2022

References
1. Nagy WW, Goldstein GR. Facebow use in clinical prosthodontic practice. J Prosthodont. 2019;28:772–4.
2. Greven M, Cazacu I, Piehslinger E. Correlation of occlusal-plane-inclination with functional condylar displacement in different skeletal classes. Int J Dent Oral Health. 2020;6(3):321.
3. Kim S-J, Lee K-J, Yu H-S, Jung Y-S, Baik H-S. Three-dimensional effect of 3D profile: Standard deviation.
4. Proffit WR, Fields HW, Larson BE, Sarver DM. Contemporary Orthodontics. Amsterdam: Elsevier; 2018.
5. Petea A, Drafa S, Stefanescu C, Oancea L. Virtual facebow technique using standardized background images. J Prosthodont. 2019;121:724–8.
6. Wozasek MR, Peacock ZS, Lavu A, Goldwasser BR, Ortiz R, Resnick CM, et al. Comparison of time required for traditional versus virtual orthognathic surgery treatment planning. Int J Oral Maxillofac Surg. 2016;45:1065–9.
7. Mavelli TC, Suporno MS, Kattadiyil MT, Goodacre CJ, Bajani K. In vitro comparison of the maxillary occlusal plane orientation obtained with five facebow systems. J Prosthodont. 2015;14:566–73.
8. Nkenke E, Zachow S, Benz M, Maier T, Viet K, Kramer M, et al. Fusion of computed tomography data and optical 3D images of the dentition for stereotactically correct positioning in the simulation of orthognathic surgery. Dentomaxillofac Radiol. 2004;33:226–32.
9. Ayoub A, Xiao Y, Khambay B, Siebert J, Hadley D. Towards building a photo-realistic virtual human face for cranio-maxillofacial diagnosis and treatment planning. Int J Oral Maxillofac Surg. 2007;36:423–8.
10. Kim BC, Lee CE, Park W, Kang SH, Zhengguo P, Yi CK, et al. Integration accuracy of digital dental models and 3-dimensional computerized tomography images by sequential point- and surface-based markerless registration. Oral Surg Oral Med Oral Pathol Oral Radiol Endod. 2010;110:370–8.
11. Lepidi L, Galli M, Manstrangelo F, Venezia P, Joda T, Wang HL, et al. Virtual articulators and virtual mounting procedures: where do we stand? J Prosthodont. 2021;30:24–35.
12. Gateno J, Xia JJ, Techgraeber JF. New 3-dimensional cephalometric analysis for orthognathic surgery. J Oral Maxillofac Surg. 2011;69:606–22.
13. Hassan B, Gimenez Gonzalez B, Tahmaseb A, Greven M, Wismeijer D. A digital approach integrating facial scanning in a CAD-CAM workflow for complete-mouth implant-supported rehabilitation of patients with edentulism: a pilot clinical study. J Prosthodont. 2017;11:478–92.
14. Lin WS, Harris BT, Phasuk K, Llop DR, Morton D. Integrating a facial scan, virtual smile design, and 3D virtual patient for treatment with CAD-CAM ceramic veneers: a clinical report. J Prosthodont. 2018;119:200–5.
15. Rangel FA, Maal TJ, Berge SJ, van Vlijmen OJ, Plooij JM, Schuys ter F, et al. Integration of digital dental casts in 3-dimensional facial photographs. Am J Orthod Dentofacial Orthop. 2008;134:820–6.
16. Rosati R, De Menezes M, Rossetti A, Sforza C, Ferrario VF. Digital dental cast placement in 3-dimensional, full-face reconstruction: a technical evaluation. Am J Orthod Dentofacial Orthop. 2010;138:84–8.
17. Xiao Z, Liu Z, Gu Y. Integration of digital maxillary dental casts with 3D facial images in orthodontic patients: a three-dimensional validation study. Angle Orthodontist. 2019;90:397–404.
18. Lam WY, Hsung RT, Choi WW, Luk HW, Pow EH. A 2-part facebow for CAD-CAM dentistry. J Prosthodont. 2016;11:843–7.
19. Solaberrieta E, Gar mendia A, Minguiez R, Brizuela A, Pradies G, Virtual facebow technique. J Prosthodont. 2015;11:751–5.
20. Li J, Chen Z, Decker AM, Wang HL, Joda T, Mentonca G, et al. Trueness and precision of economical smartphone-based virtual facebow records. J Prosthodont. 2021.
21. Lam WYH, Hsung RTC, Choi WWS, Luk HWK, Cheng LYY, Pow EHN. A clinical technique for virtual articulator mounting with natural head position by using calibrated stereophotogrammetry. J Prosthodont. 2018;119:902–8.
22. Lin X, Chen T, Liu J, Jiang T, Yu D, Shen SJ. Point-based superimposition of a digital dental model on to a three-dimensional computed tomographic skull: an accuracy study in vitro. Br J Oral Maxillofac Surg. 2015;53:28–33.
23. Baan F, Liebregts J, Xi T, Scheurers R, de Koning M, Berge S, et al. A new 3D tool for assessing the accuracy of bimaxillary surgery: the OrthoGnathic Analyser. PLoS ONE 2016;11:e0149625.
24. Bechtold PE, Götz TG, Schau ppm, Koos B, Godt A, Reinent S, et al. Integration of a maxillary model into facial surface stereophotogrammetry. J Orofac Orthop. 2012;73:126–37.
25. Ackerman J, Proffit W, Sarver D, Ackerman M, Kean M. Pitch, roll, and yaw: describing the spatial orientation of dentofacial traits. Am J Ortho dentofacial Orthop. 2007;131:305–10.
26. D’Etto G, Faronato M, Candida E, Quinzi V, Grippaudo C. A comparison between stereophotogrammetry and smartphone structured light technology for three-dimensional face scanning. Angle Orthod. 2022;92:358–63.
27. Verhuls A, Hol M, Veeneken R, Becking A, Ulrich D, Maal T. Three-dimensional imaging of the face: a comparison between three different imaging modalities. Aesthet Surg J. 2018;38:579–85.
28. Michelinakis G, Apostolakis D, Tsagarakis A, Kourakis G, Pavlakis E. A comparison of accuracy of 3 intraoral scanners: a single-blinded in vitro study. J Prosthet Dent. 2020;124:581–8.

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.