Recording and Transferring Head Positions to the Virtual Head Using a Multicamera System and Laser Level

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Purpose: To fulfill the requirements of computer-aided orthognathic surgery, the authors developed a method of recording head positions in pitch and roll and tested its accuracy and reliability.

Materials and Methods: A laser level was used to project a horizontal laser line onto a volunteer's face. A 3-dimensional (3D) photograph of the volunteer was taken to capture the laser line using the 3dMDface System, so the head positions could be recorded. To test the accuracy and reliability of this method, 35 head positions were recorded and compared with the positions recorded by the gyroscope method (P_n for pitch and R_n for roll). A cone-beam computed tomographic (CBCT) scan was taken, during which the head position was recorded by the gyroscope (P_0 and R_0). CBCT data were imported into ProPlan CMF 1.3 software and a virtual head was created. To reproduce each recorded head position, each 3D photograph was superimposed onto the virtual head through surface registration, and the virtual head was rotated to make the laser line parallel to the coordinate axes in the lateral and frontal views; the rotation angles were recorded, respectively, as P_n' and R_n'. Under ideal conditions, P_n' should equal $P_n - P_0$ and R_n' should equal $R_n - R_0$. The accuracy was evaluated using the Bland-Altman method. Reliability was tested by intraclass correlation coefficient (ICC) analysis.

Results: The 95% limits of agreement between the rotation angles recorded by the present method (P_n', R_n') and the gyroscope method ($P_n - P_0$, $R_n - R_0$) were $-0.598°$ to $1.589°$ for pitch and $-1.156°$ to $1.674°$ for roll; such a difference was generally accepted as being accurate. The ICCs were 0.996 (0.992, 0.998) for pitch and 0.998 (0.997, 0.999) for roll.

Conclusion: The 3dMDface System and laser level method of recording head positions was accurate and reliable.

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With the development of computer-aided surgical simulation (CASS) for orthognathic surgery, the choice of a reference plane has concentrated on the Frankfort horizontal (FH) plane[1] and the true horizontal plane based on the natural head position (NHP).[2,3] The FH plane has become the most important reference plane, especially in traditional cephalometry based on lateral radiographs, since the Craniometrical Conferences in the 1880s.[4] In traditional cephalometry, the FH plane is a line; however, when used as a reference plane in 3-dimensional (3D) virtual design, the flaws of the FH plane gradually emerged, including

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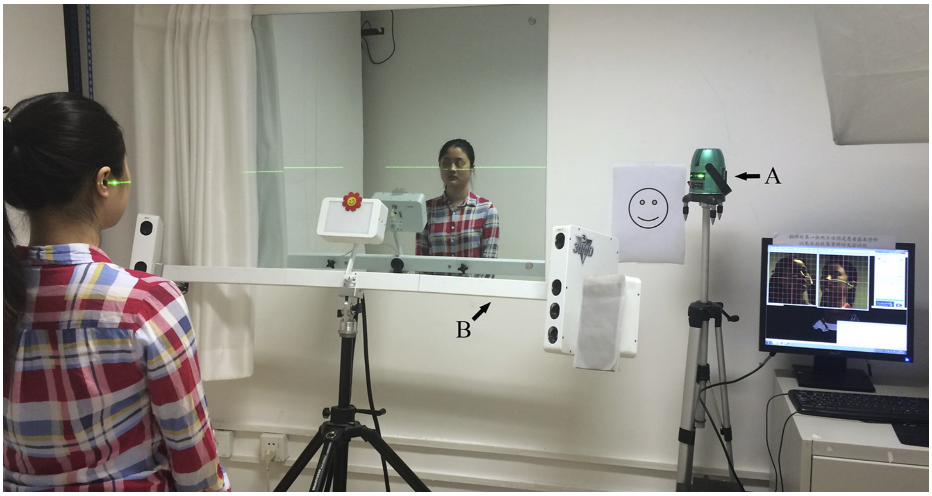

FIGURE 1. Setting and instruments used to record head positions. *A*, Laser level. *B*, The 3dMDface System. The center flashlight was turned off, and the right and left flashlights were covered with translucent paper to decrease the intensity of the light.

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considerable individual variation,[5] confusion as to how to define the plane, and distortion caused by craniofacial deformity.[6]

As a result of the good reproducibility of NHP, which has been reported by many investigators in the sagittal and coronal planes,[7-11] it has been used to provide a coordinate system for cephalometric analysis, surgical design, and tracking facial growth patterns.[6,12,13] Most traditional methods for recording the NHP are based on 2-dimensional radiographs or photographs[7,9,14,15] and are not suitable for 3D virtual design. To fulfill the need of CASS for orthognathic surgery,[16,17] many studies have focused on recording the NHP in 3 dimensions.[12,18-21] Although these methods are feasible for recording the NHP, some involve computed tomographic (CT) scans[12,18,21] and some procedures are inconvenient for clinical use.[19,20] Therefore, developing a convenient and accurate method to record the NHP without radiation exposure is imperative.

Based on previous studies, the authors developed a method to record head positions by capturing a 3D image of a subject's face while a horizontal laser line is projected on to the subject's face. Whether this new method could be used in clinical practice needed to be investigated. Therefore, this study was

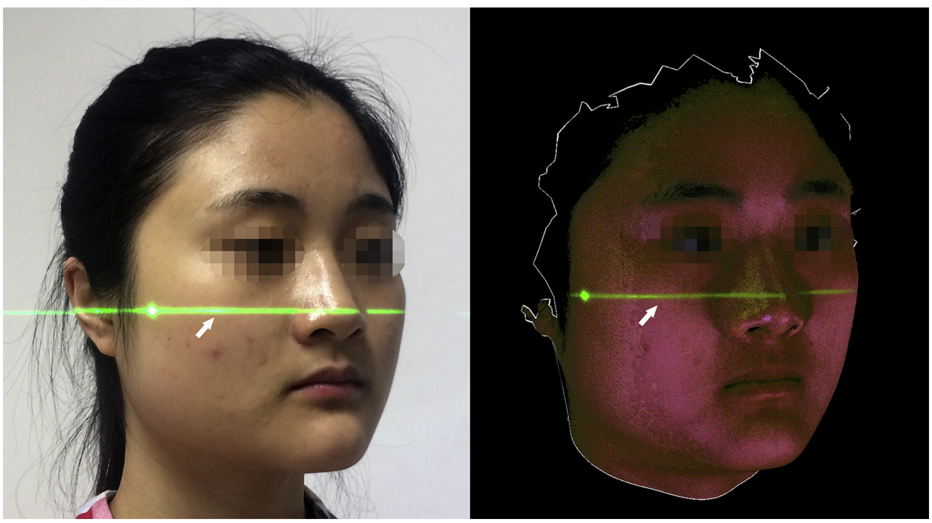

FIGURE 2. Three-dimensional imaging of the head position. The head position was recorded by capturing a 3-dimensional photograph of the volunteer with the laser line (*arrows*) projected onto the face. The *horizontal laser line* was clearly captured and could be easily recognized on the 3-dimensional photograph (*right*).

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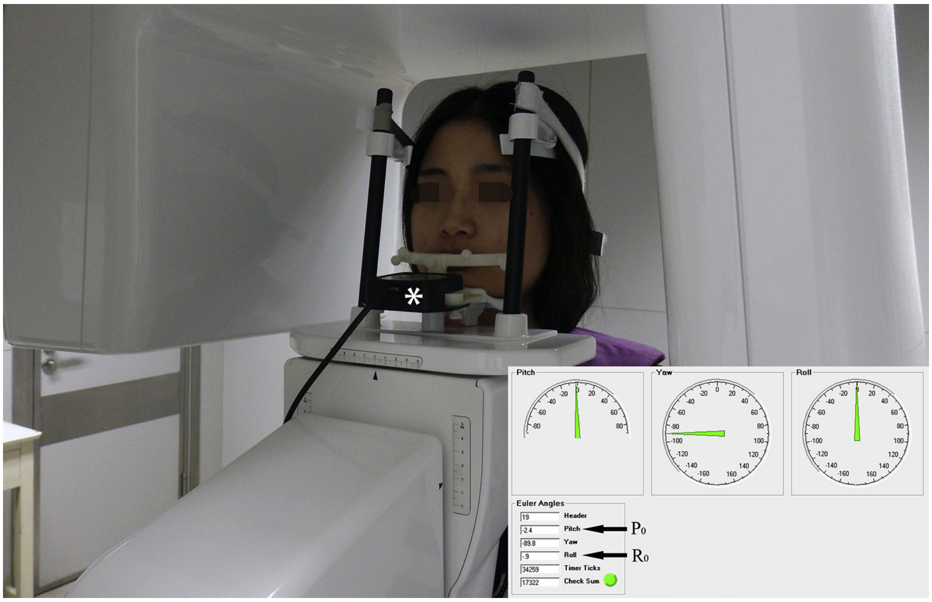

FIGURE 3. Cone-beam computed tomographic scanning of the volunteer. The head position of the volunteer during scanning was recorded by the digital gyroscope (*asterisk*). *Arrows* show the recordings of the head position (P_0 and R_0). P_0, pitch; R_0, roll.

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conducted to test the reliability and accuracy of this new protocol for clinical use.

Materials and Methods

A healthy volunteer (a 23-yr-old woman) who was not pregnant and had signed the informed consent was included in this study. This study was approved by the institutional review board of the Peking University School of Stomatology (Beijing, China; PKUSSIRB-201413039) and followed the Declaration of Helsinki on human research.

NEW TECHNIQUE TO RECORD HEAD POSITION

The new technique used a SW902 laser level (Saiwei, Shanghai, China; Fig 1A) and the 3dMDface System (3dMD Inc, Atlanta, GA; Fig 1B). As the manufacturer's handbook stated, the wavelength of the laser was 635 nm, with a horizontal accuracy of 0.2 mm/m. The 3dMDface System could capture an image of the entire face (from ear to ear). The capture speed was 1.5 ms with a resolution of 400 dpi, and the accuracy was 1.5% of the total observed variance. The procedure to record the head position is described below.

The laser level was set up beside the 3dMDface System, and the height of the laser level was adjusted so that the horizontal laser line projected onto the face of the participant in the area from the nasal apex to the infraorbital margin. When the height of the laser level was adjusted, the participant was asked to sit straight with her eyes closed to protect them from the laser and was informed not to stare into the beam. The participant sat in front of the 3dMDface System, and her position was adjusted to display her face in the center of the viewing window. The distance between the participant and the laser level was approximately 1.5 m (Fig 1). Then, the center flashlight of the 3dMDface System was turned off to acquire a clearer laser line on the obtained images. When the head position of the participant was acquired, the laser level was turned on and the head position was recorded by capturing a 3D photograph with the horizontal laser line on the face (Fig 2).

STUDY DESIGN

To test the reliability and accuracy of the new method, 35 random head positions of the volunteer were recorded with the new method and with a digital gyroscope (3DM; MicroStrain, Williston, VT) simultaneously.

GYROSCOPE METHOD TO RECORD HEAD POSITION

The accuracy of the digital gyroscope to record head positions is well established.[12,18,22] Therefore, it was used as the standard method for recording head positions. The procedure to record head positions with the gyroscope, as introduced by Xia et al,[18] is described below.

First, the individualized bite registration of the volunteer was obtained on a bite jig using a LuxaBite (Chemisch-Pharmazeutische Fabrik GmbH, Berlin, Germany).

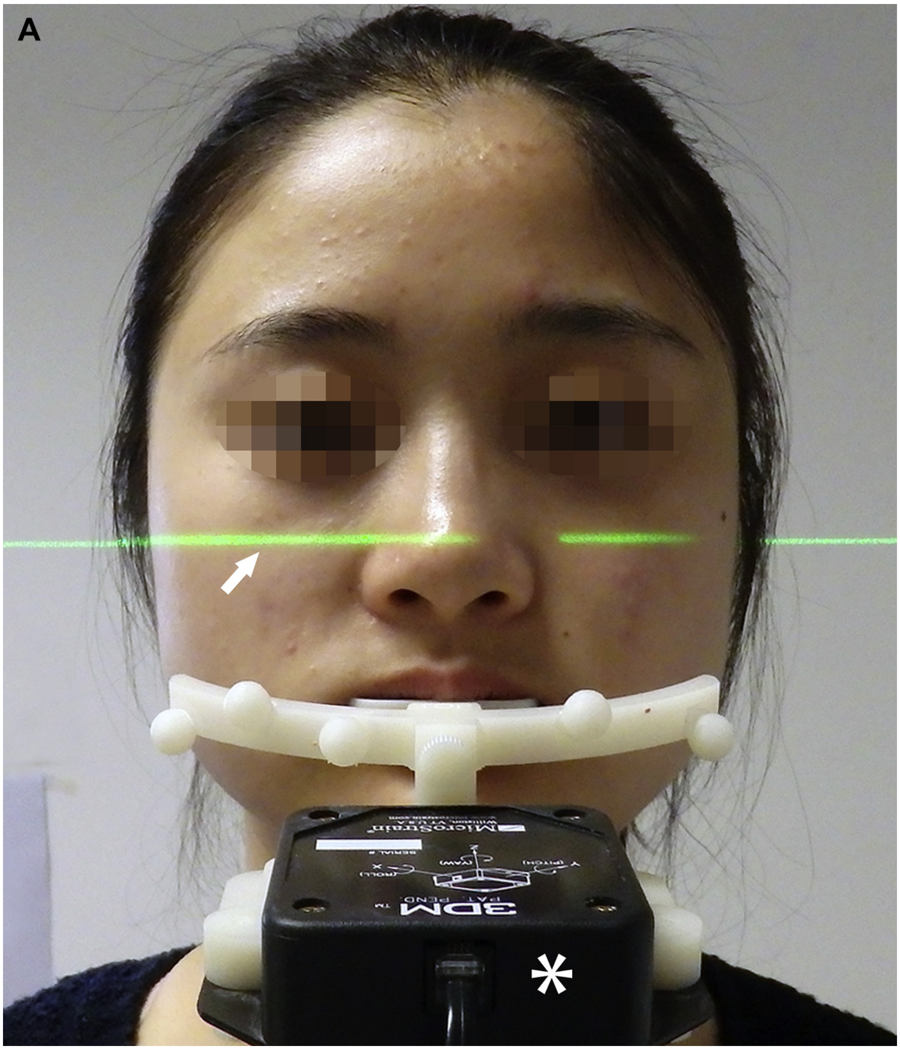

FIGURE 4. Recording head positions using the 2 methods. Each test head position was simultaneously recorded by the digital gyroscope (*asterisk*) and by the 3dMDface System and laser level. *A*, Frontal view show the horizontal laser line (*arrow*) projected on the face and **(Fig 4 continued on next page.)**

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Second, the bite jig was assembled with the facebow (Medical Modeling Inc, Golden, CO) and the digital gyroscope. The entire device was placed in the volunteer's mouth, and the device was bitten by the volunteer. A careful examination was performed to confirm the device was in place without obstruction or looseness.

By this procedure, the head position could be recorded from gyroscope readings, and changes in head position could be calculated by comparing the recordings of 2 different head positions.

CONE-BEAM CT SCANNING AND ESTABLISHMENT OF THE VIRTUAL HEAD

A cone-beam CT (CBCT) scanner (VG; NewTom, Verona, Italy) was used to obtain a CBCT scan of the volunteer's face. Before CBCT scanning, the gyroscope device was assembled and placed in the volunteer's mouth. Then, the CBCT scan was performed. The scanning matrix was 400 $\times$ 400 with a field of view of 15 $\times$ 15 cm and a gray-level depth of 16 bits. The layer thickness was 0.075 mm. The head position of the volunteer during the CBCT scan (CBCT position) was recorded simultaneously by the gyroscope (P_0 for pitch and R_0 for roll; Fig 3). CBCT data were transferred to ProPlan CMF 1.3 software (Materialise, Oberdorf, Switzerland), which also quoted the original coordinate system of the CBCT scan. The skin surface was created by segmenting the CBCT data.

RECORDING HEAD POSITIONS USING THE 2 METHODS

The assembled gyroscope device was placed in the volunteer's mouth and secured. Then, the volunteer

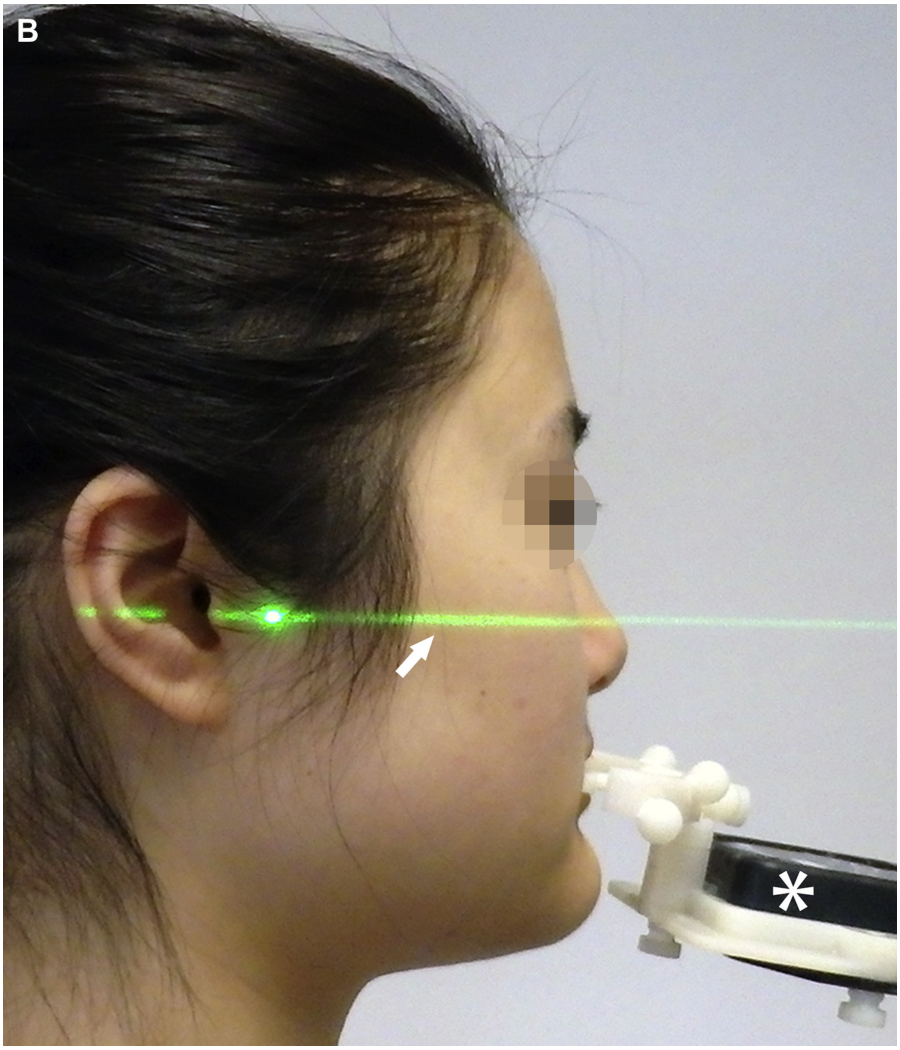

FIGURE 4 (cont'd). *B*, lateral views show the horizontal laser line (*arrows*) projected on the face. **(Fig 4 continued on next page.)**

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was positioned in front of the 3dMDface System. When her head position (test head position) was acquired, a horizontal laser line was projected onto her face, and then a 3D photograph was taken to record the head position (Fig 4). The head position also was recorded simultaneously by the digital gyroscope (P_n for pitch and R_n for roll). Thirty-five random head positions were obtained and recorded by the 2 methods simultaneously. Thirty-five pairs of P_n and R_n were obtained. The alterations from the CBCT position (P_0, R_0) to the test head position (P_n, R_n) recorded by the gyroscope could be calculated as $\Delta P_n = P_n - P_0$ and $\Delta R_n = R_n - R_0$.

REPRODUCING TEST HEAD POSITIONS IN THE SOFTWARE AND TESTING RELIABILITY AND ACCURACY OF THE NEW METHOD

The 3D photograph was saved in Virtual Reality Modeling (wrl) format and imported into ProPlan CMF 1.3 software. The 3D photograph was superimposed onto the virtual head created from the CBCT data through a surface registration procedure. During this procedure, the virtual head was set as the fixed object and the 3D photograph as the floating object. By using this procedure, the laser line was shown on the virtual head. The virtual head position was adjusted manually according to the laser line. In the software, the *x*-axis represents the transversal vector, the *y*-axis represents the sagittal vector, and the *z*-axis represents the vertical vector. Therefore, the pitch, roll, and yaw refer to the rotation around the *x*-, *y*-, and *z*-axes, respectively. The virtual head was rotated until the laser line was parallel to the *x*-axis in the frontal view and the *y*-axis in the lateral view. The coordinate axes were rechecked to be parallel to the laser line from the 2 views. By this procedure, the angles

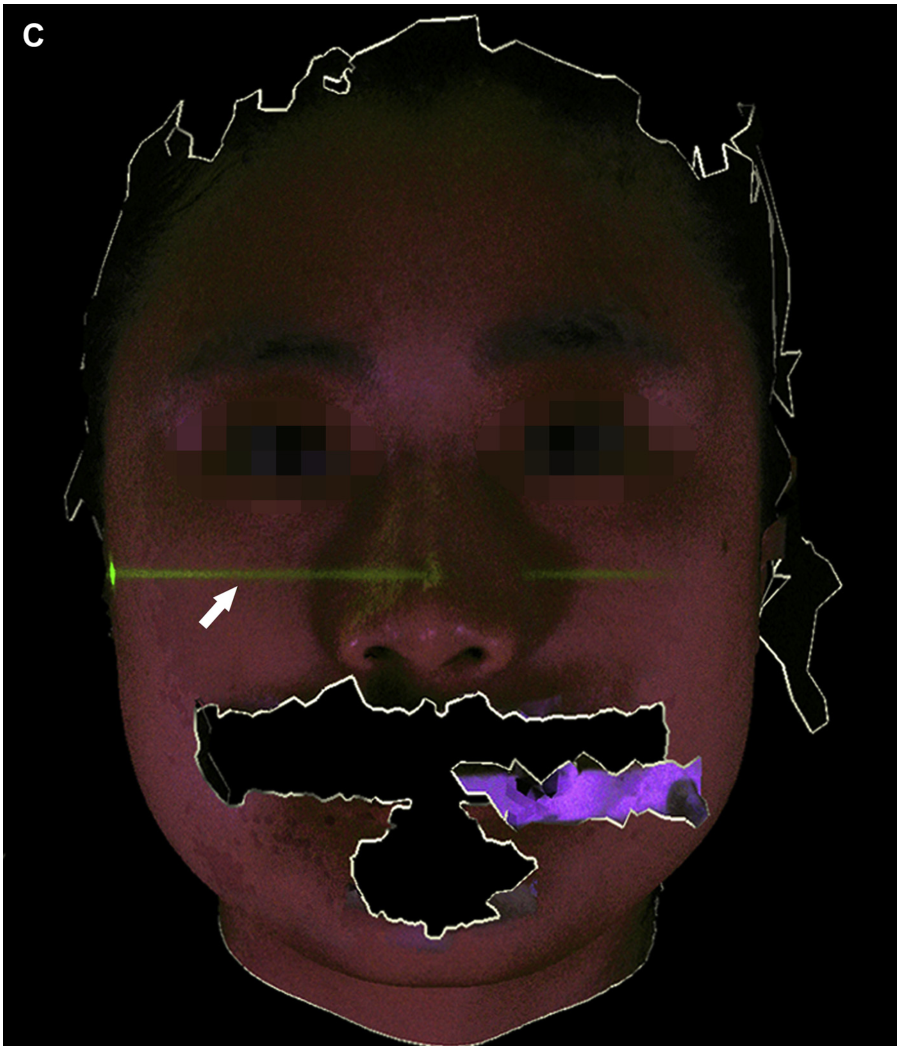

FIGURE 4 (cont'd). *C*, Frontal view of 3-dimensional photograph and **(Fig 4 continued on next page.)**

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of the virtual head rotated in the lateral and frontal views could be measured and recorded as P_n' and R_n' (Fig 5). Then, the position of the virtual head was changed to the recorded test head position. By repeating the aforementioned procedure for each test head position, 35 pairs of P_n' and R_n' were obtained. Under ideal conditions, for each test head position, P' should equal ΔP and R' should equal ΔR. The authors evaluated the differences between P_n' and ΔP_n and the differences between R_n' and ΔR_n to test the accuracy of the new method.

To assess the reliability of the method, the transferring procedure for each test head position was performed by 3 experienced orthognathic surgeons independently. The study design is shown in Figure 6.

STATISTICAL ANALYSIS

SPSS 19.0 (SPSS, Inc, Chicago, IL) was used to perform intraclass correlation coefficient (ICC) analysis. A 2-way mixed effect model for the ICC was used to test reliability. An ICC value from 0.8 to 1.0 was considered almost perfect agreement, and a value from 0.6 to 0.8 was considered substantial agreement.[23] If the measurements were almost perfectly repeatable, the averages of the 3 measurements were used to test the accuracy of the present method compared with the standard method.

The data were normally distributed. The Bland-Altman method was used to test agreement between the present method and the standard method.[24] Considering the studies on the reproducibility of the

FIGURE 4 (cont'd). *D*, lateral views of 3-dimensional photograph.

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NHP, a difference greater than 2° was considered meaningfully different.[4,25,26] MedCalc 15.2.2 (MedCalc, Ostend, Belgium) was used to perform the Bland-Altman method.

Results

The ICC values for the reliability test for the 3 operators were 0.996 (95% confidence interval [CI], 0.992 to 0.998) for pitch and 0.998 (95% CI, 0.997 to 0.999) for roll. These results indicated an almost perfect agreement among the 3 operators. Therefore, the averages of the 3 measurements were used to test accuracy.

The results of Bland-Altman method showed the lower and upper limits of agreement between the 2 methods were −0.598° to 1.589° for pitch and −1.156° to 1.674° for roll, which indicated no clinically important difference (Table 1).

Discussion

With the development of computer technology, CASS has gained popularity in orthognathic surgery and is gradually replacing the traditional plaster model surgery and 2-dimensional cephalometry analysis.[2,6] A virtual design procedure is typically based on 3D CT data. In this procedure, it is important that the virtual skull should be oriented in the NHP.[27,28] The NHP also is important in postoperative follow-up, especially when the change of the NHP needs to be assessed and facial asymmetry needs to be re-evaluated in the same coordinate system.[29,30]

A

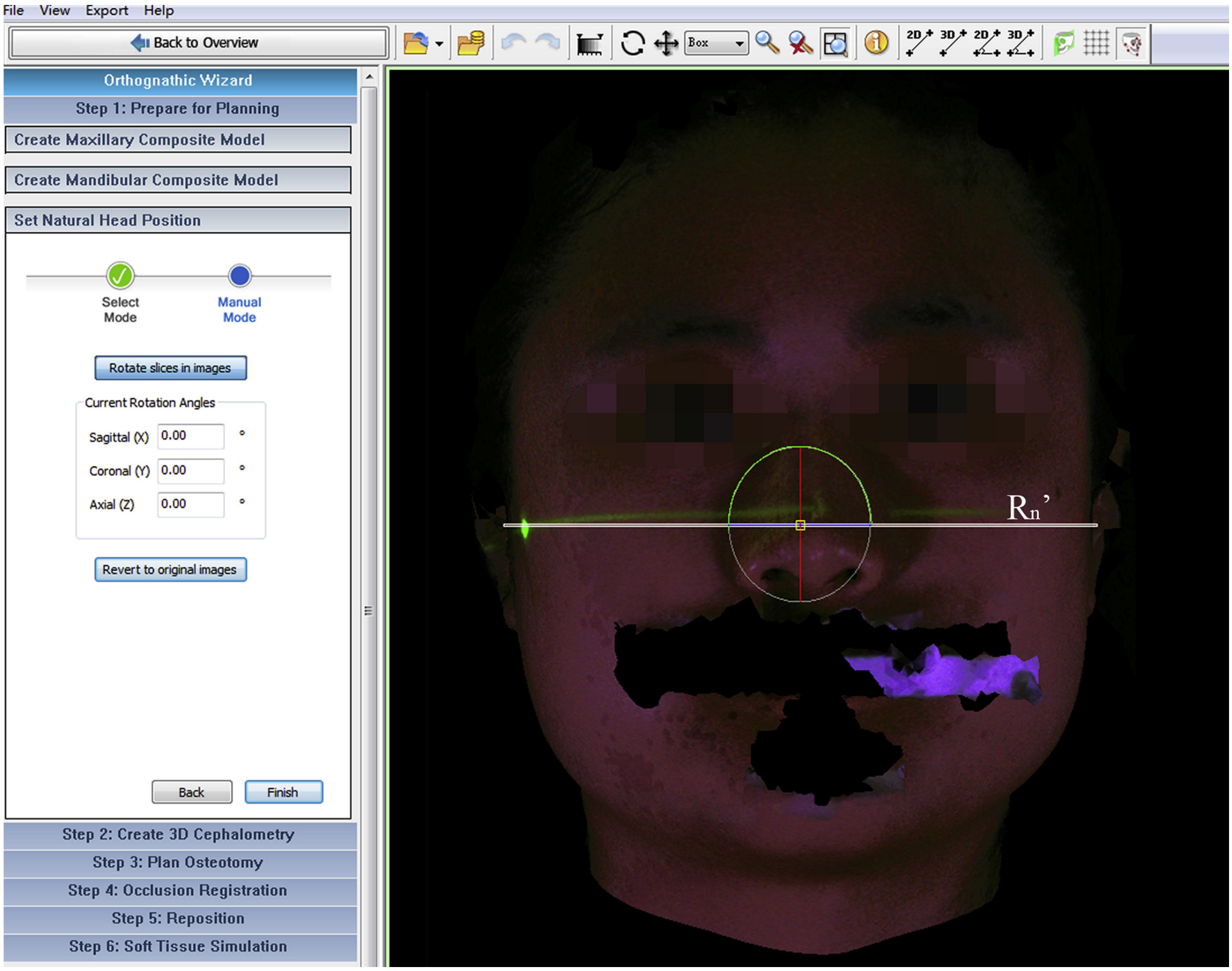

FIGURE 5. Reproducing the test head position using the authors' method. Each test head position was reproduced by manual adjustment in ProPlan CMF 1.3 software according to the horizontal laser line. Changes in head orientation were calculated and displayed in real time in the dialog box (*arrows*). After the 3-dimensional photograph was superimposed onto the virtual head, an inclination of the laser line could be observed in the *A*, frontal and **(Fig 5 continued on next page.)**

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Schatz et al[12] and Xia et al[18] used a digital gyroscope to record the NHP for virtual surgical design. This method proved accurate for recording head positions and was chosen as the standard method for comparison with the authors' new method for recording head positions. However, with the digital gyroscope method, if the NHP needed to be recorded and reproduced during the follow-up period, then the patient had to undergo repeated CT scans for each new measurement. This repeated scanning could increase radiation exposure for patients to unacceptable levels.

Kim et al[21] developed a novel method for recording NHP based on "pose from and scaling with iterations" (POSIT) technology using a single frontal facial photograph to record the 3D NHP. This method was time effective and required no extra instruments and might be convenient for orthognathic surgery. However, this method involved a camera set in front of the patient when acquiring the NHP, which could obstruct the patient's line of sight, and their method might be improved by combining it with the method reported by Dong et al.[31] Furthermore, the need for CT scanning might prohibit the use of this method during postoperative follow-up.

Hsung et al[20] reported a method to record NHP using the 3dMDface System. In this method, a finely adjusted reference board was imaged to provide a coordinate reference for orienting the virtual head to the NHP. Compared with that study, the present method is more feasible and practical, with no need for adjustment of the reference board, which took 10 to 15 minutes in the study by Hsung et al.

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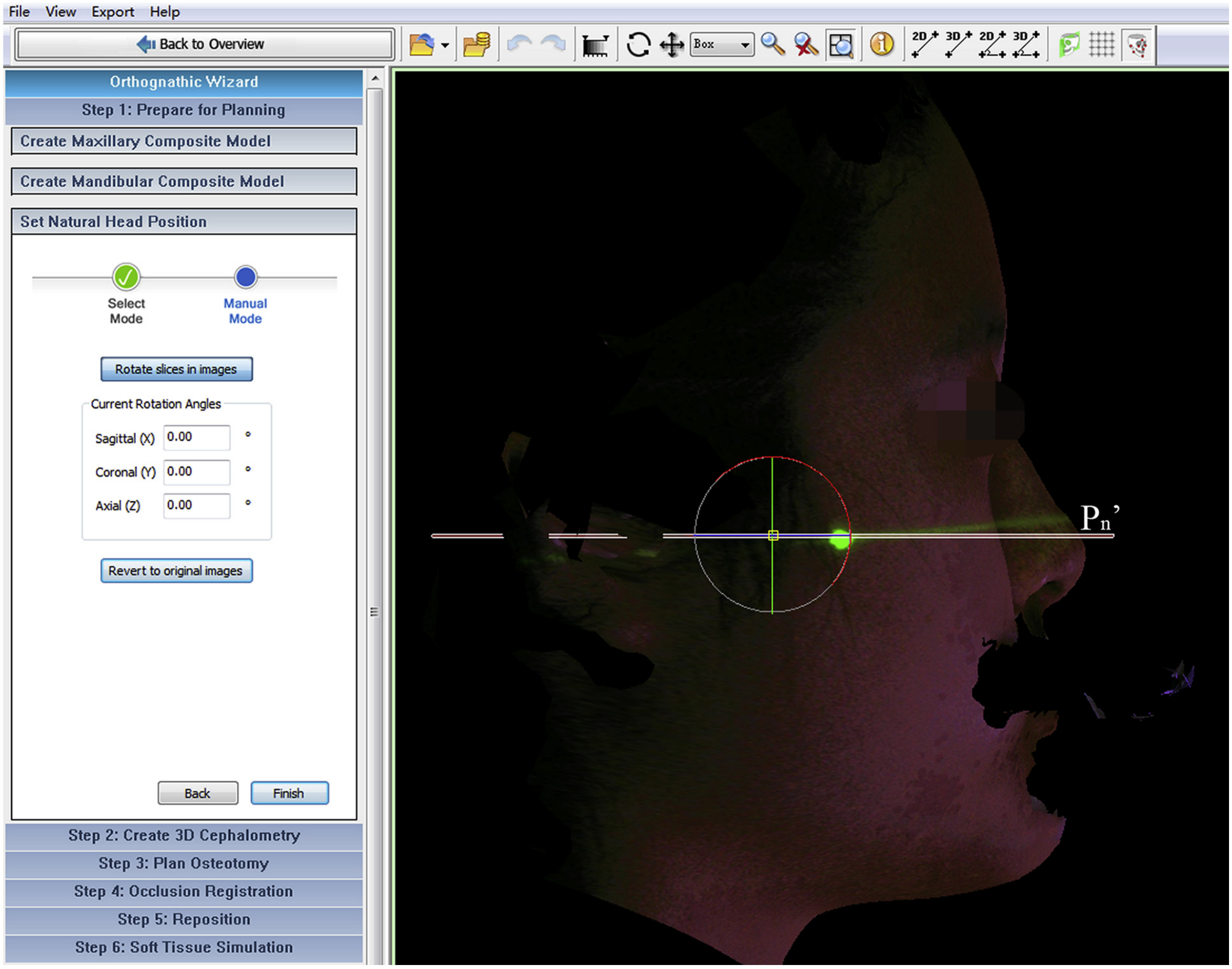

FIGURE 5 (cont'd). *B*, lateral views. **(Fig 5 continued on next page.)**

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Weber et al[19] also introduced a method to record the NHP with a 3D camera system. They projected horizontal and vertical laser lines on the subject's face while the NHP was acquired. Then, they placed 4 ink dots on the subject's face to mark the laser lines. A 3D photograph of the subject was taken to capture the reference points using the 3D camera system. This allowed the NHP of the subject to be recorded without the need for radiation exposure and occlusion connection. However, the accuracy of this method might be influenced by slight movements of the head when the ink dots are applied by the doctor. The separate procedure of registering and recording the NHP also might make this method inconvenient for patients and doctors.

To fulfill clinical requirements, a proper method to record the NHP should be accurate, reproducible, operator independent, and not influence the head position while the NHP is recorded.[32] Previous studies recorded the NHP based mainly on lateral cephalometric radiographs or photographs using a suspended vertical wire beside the subject or a horizontal line on the wall for reference.[7,8,14,33-35] Although these methods were not suitable for 3D virtual design, the principle of recording the image together with the reference lines remains useful. A similar principle was adopted in this study, and a horizontal laser line was recorded together with the 3D photograph.

Because the laser line was directly projected onto the face and might lead to eye injuries, laser safety must be considered. Lasers were classified by wavelength and maximum output power according to the IEC 60825-1 standard.[36] Lasers with a wavelength from 400 to 700 nm and power within 1 mW are classified as Class 2 and are safe for clinical use, although patients should not stare into the beam. According

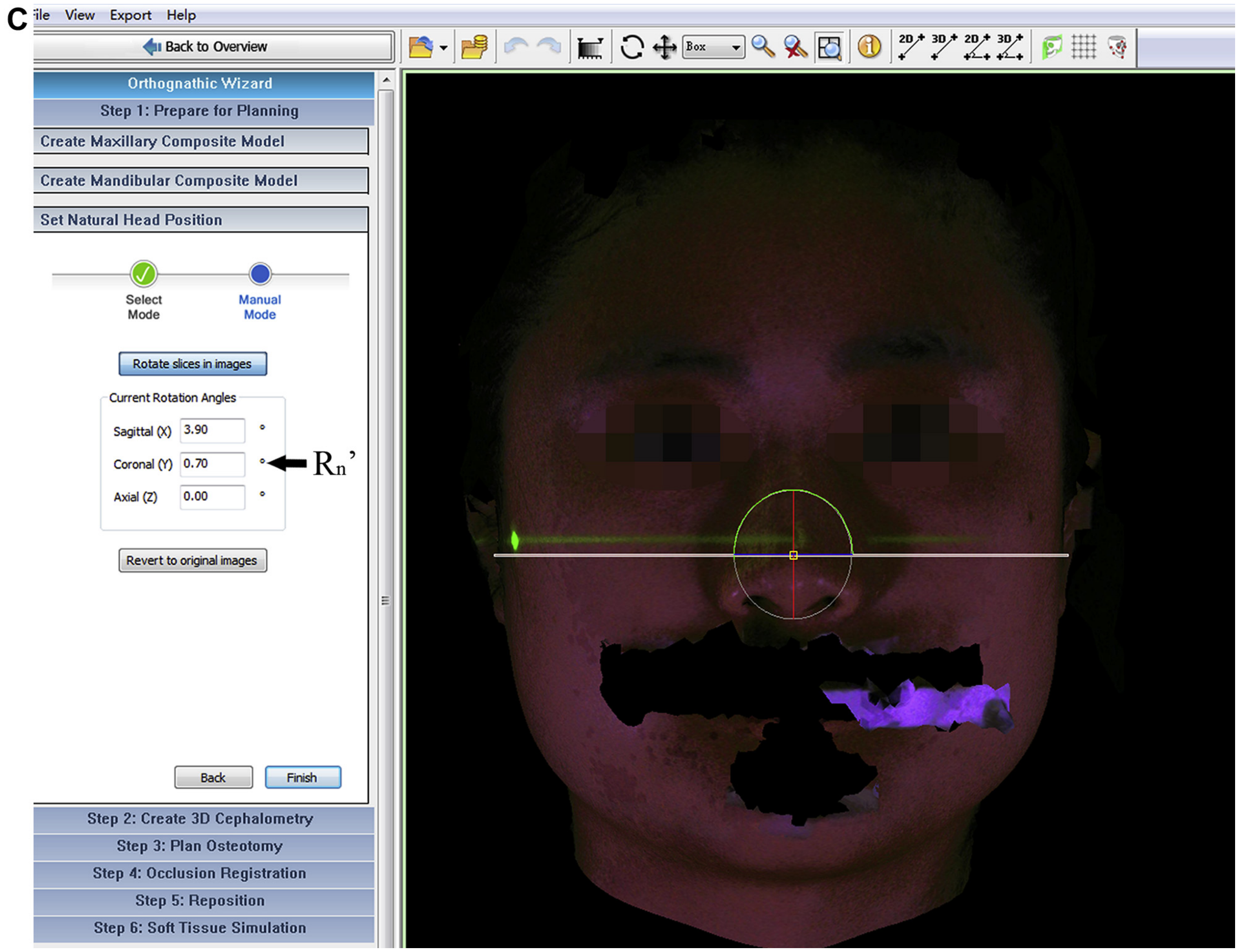

FIGURE 5 (cont'd). *C*, First, the virtual head was rotated in the frontal view so that the laser line was parallel to the *x*-axis. *Arrow* shows the rotation angle (R_n') in the frontal view. **(Fig 5 continued on next page.)**

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to the manufacturer's handbook, the laser in this study is a Class 2 laser. It should be noted that, in the first step of recording the head positions using the present method, the height of the laser level should be adjusted to make sure the laser line is not be projected into the eyes; during this procedure, the patient should sit up straight with the eyes closed. The patient also should be informed to not stare into the beam.

In this study, manual alignment of the coordinate axes to the horizontal laser line was required when orienting the virtual head to the recorded head position, which might introduce errors. The results of the present study show that this method is highly reliable, with ICC values higher than 0.99 among different operators for pitch and roll. The reason for the high reliability might be that the laser line could provide more information for orienting the virtual head compared with the ink dots used in the method of Weber et al.[19] The high reliability also indicates that the laser lines on 3D photographs could be identified without confusion.

The Bland-Altman method showed that mean differences between the present method and the gyroscope method for recording and reproducing head positions were 0.496° for pitch and 0.259° for roll, with the lower and upper limits of agreement less than 2° apart, indicating a clinically acceptable accuracy.[18,25] This method also is feasible and convenient for clinical use, involves no radiation exposure, and would be feasible for evaluation of postoperative soft tissue changes. The mean difference in pitch was larger than the mean difference in roll. The authors hypothesize that this might be due to the fact that, on occasion, the 3D photographs did not display the

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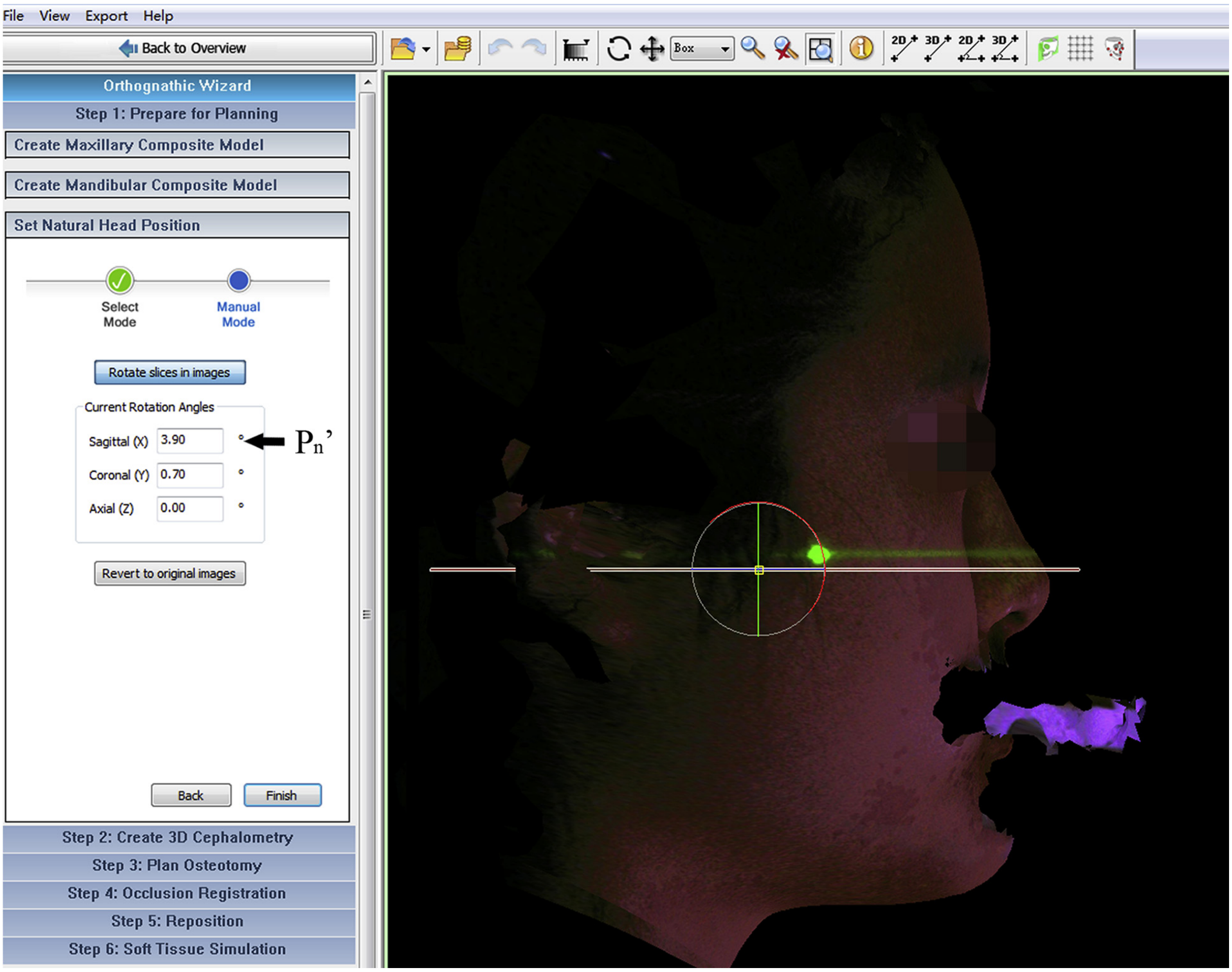

FIGURE 5 (cont'd). *D*, Second, the virtual head was rotated in the lateral view so that the laser line was parallel to the *y*-axis. *Arrow* shows the rotation angle (P_n') in the lateral view.

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lateral view clearly; black hair in the lateral view might reflect less light and thus an accurate image might not be captured effectively. This might shorten the recognizable laser line in the lateral view. Therefore, greater accuracy could be expected by using another laser level to project a laser line from the side and avoid this problem in future clinical use.

To the authors' knowledge, the 3dMDface System has become more popular in recent years. More and more hospitals have their own 3dMDface System machines for acquiring digital data of patients and to improve their virtual design and clinic skills and therefore might use the present method to record the NHP. However, because the price of the 3dMDface System is much higher than that of the gyroscope, its cost might be a problem for those units that would need to purchase the 3dMDface System specifically for this method.

In the present study, an imaging method using a laser level and the 3dMDface System to record head positions in pitch and roll was introduced and proved accurate and reliable. Because the NHP is a specific position that is standardized and reproducible,[37] it could be recorded using this method. Once the NHP of the patient is acquired, this method using a laser level and the 3dMDface System could be used to provide a reference plane for orthognathic surgery.

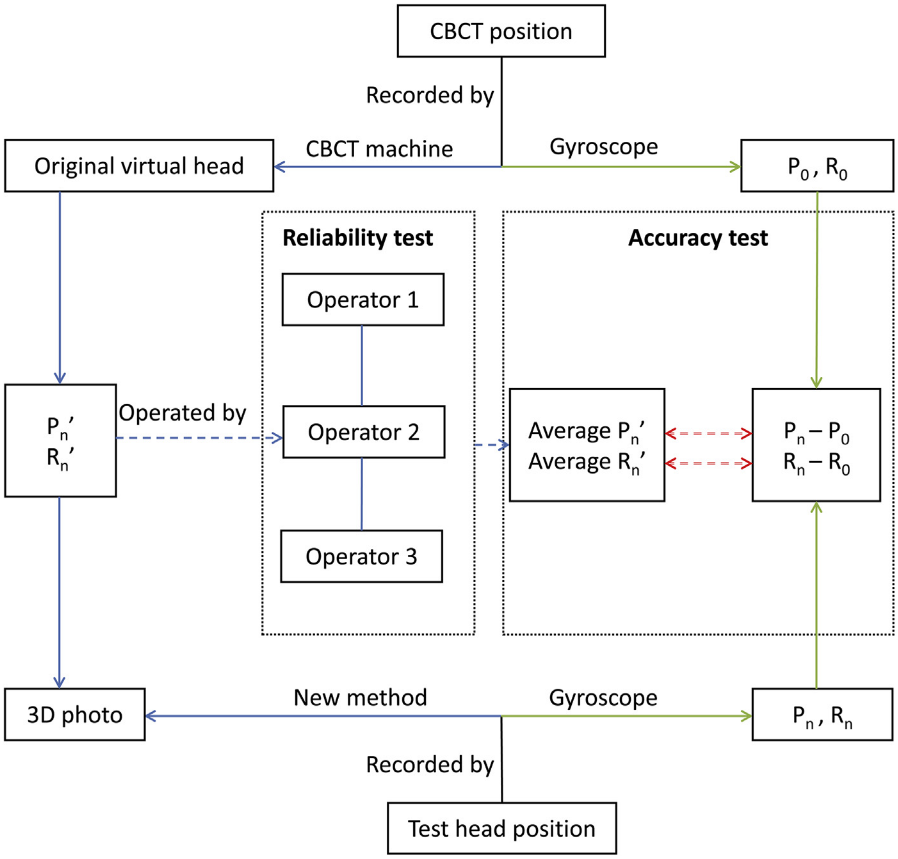

FIGURE 6. Workflow and study design. The head position of the volunteer during the CBCT scan (CBCT position) was recorded by the CBCT machine and by the gyroscope (standard method, P_0 for pitch and R_0 for roll). A virtual head was generated from the CBCT data. The authors' method, using a laser level and the 3dMDface System, was used to generate a 3D photograph of the test head position, which also was recorded by the gyroscope (P_n and R_n). When reproducing each test head position recorded by the 3D photograph, the rotation angles in the lateral view (P_n') and frontal view (R_n') could be recorded. This procedure was performed by 3 independent operators. Reliability among them was tested. If the reliability test was approved, then the average pitch and roll for each image was calculated and compared with the standard method. 3D, 3-dimensional; CBCT, cone-beam computed tomographic.

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Table 1. ACCURACY OF AUTHORS' METHOD COMPARED WITH STANDARD METHOD

	Mean (95% CI)	SD	Lower Limit of Difference (95% CI)	Upper Limit of Difference (95% CI)
Pitch	0.496 (0.304-0.687)	0.558	−0.598 (−0.928 to −0.267)	1.589 (1.258-1.920)
Roll	0.259 (0.011-0.507)	0.722	−1.156 (−1.584 to −0.728)	1.674 (1.246-2.102)

Abbreviations: CI, confidence interval; SD, standard deviation.

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