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Automatic Reproduction of Natural Head Position Using a Portable 3D Scanner Based on Immediate Calibration

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Abstract: This paper developed a new method to easily record and automatically reproduce the 3D natural head position (NHP) of patients using a portable 3D scanner based on immediate calibration. We first optically scanned the patient's face using a portable 3D scanner, and the scanned model was easily aligned with the global horizon based on an immediate calibration procedure using a developed calibration plate. The 3D patient NHP Computed Tomography(CT) model was reproduced automatically by performing registration between the CT model and the optically scanned model in the NHP using a modified coherent point drift (CPD) algorithm. In a phantom experiment, we evaluated the developed method's accuracy using the error between the true and the calculated orientations in roll, pitch, and yaw directions. The mean difference was −0.05 ± 0.13°, 0.08 ± 0.22°, and −0.05 ± 0.18° in the roll, pitch, and yaw directions, respectively. The measured roll, pitch, and yaw directions were not significantly different from the true directions ($p > 0.05$). The calibration procedure for aligning the scanner coordinate system was easy enough for an inexperienced user to operate, and the 3D NHP CT model could be reproduced automatically. The developed method could be used for diagnosing and treating orthognathic patients with facial asymmetry accurately and conveniently in dental clinics.

Keywords: natural head position (NHP); orthognathic surgery; optical 3D scan; coherent point drift (CPD) registration

1. Introduction

It is important to acquire the correct head position accurately to improve orthognathic surgery outcomes [1]. To obtain the correct head position, the natural head position (NHP), in which the head is positioned upright with the eyes focused on a distant point at eye level, has been introduced [2,3]. Previously, intracranial cephalometric landmarks were used as a logical reference for evaluating the orthodontic facial morphology in two-dimensional (2D) cephalometric analyses [4–6]. Recently, a three-dimensional (3D) NHP reproduction method has been introduced [7]. An important factor for diagnosing and treating orthognathic patients with severe facial asymmetry is the rotation of the patient's 3D skull model to the NHP [1]. However, the 3D skull model cannot be rotated to the NHP

using intracranial landmarks and planes for craniomaxillofacial patients with severe asymmetry [8]. Clinical CT images of patients do not represent the NHP because the patient head is oriented randomly in the CT coordinate system during CT scanning [9]. Therefore, a general CT image does not reflect the patient's NHP in clinical practice [9]. To overcome this limitation of CT imaging for the diagnosis and treatment of orthognathic patients, several studies have been conducted to record 3D NHPs [1,9–14].

In one method, the authors recorded the 3D NHP using an orientation or gyroscope sensor mounted on a personalized bite jig [1,10,11]; however, the weight of the sensor caused distortions in the shape of the lips [9,12]. Since the position of the upper lip significantly affects predictions regarding soft tissue changes during 3D surgical simulations, the shape of the lips should not be deformed in computer-assisted orthognathic surgery [8–11]. In another method, the CT model was rotated to the 3D NHP using the position of the radiopaque stickers attached to the horizontal and vertical laser lines on the face to avoid changing the shape of the lips [12]. In another method, the 3D NHP of the CT model was reproduced by a pose from orthography and scaling with iterations (POSIT) algorithm using a common 2D digital camera and ceramic markers [9]. The limitation of these studies was the need to attach fiducial markers to the patient's face for NHP recording. As the positions of these fiducial markers were manually extracted in the 3D CT model, the accuracy of the NHP reproduction might have been influenced by the extracted positions of the fiducial markers. Moreover, the POSIT algorithm might fail in planar configuration of marker points on the patient face [15]. In recent methods, the 3D NHP of CT models was recorded without affecting the patient's face and was reproduced using 3D scanned images obtained using a stereophotographic system [13,14]. The methods based on the stereophotographic system required thecalibration or alignment of the scanner coordinate system with a physical reference using a reference board or a laser level device. However, the calibration procedure for the system was complex and time-consuming, and the system to scan the patient was difficult to install and bulky.

In the previous studies, the patient's head was optically scanned in the NHP with markers or sensors attached to the patient, or the calibration or alignment of the scanner coordinate system was complex and time-consuming. Therefore, the aim of this paper is to develop a new method to easily record and automatically reproduce the 3D NHP of CT models without soft tissue changes of the patient using a portable 3D scanner based on immediate calibration.

2. Materials and Methods

2.1. Patient's CT Scanning and NHP Recording Using a Portable 3D Scanner

The CT images of five patients were acquired using an MDCT scanner (SOMATOM Sensation10, Siemens, Munich, Germany) under 120 kVp and 80 mAs with a slice thickness of 0.75 mm. After CT scanning, the calibration plate was attached to the wall with its horizontal level adjusted to be parallel with the global horizon using a digital spirit level (DLX360, Yato, Shanghai, China). Next, we optically scanned the calibration plate using a portable 3D scanner based on a structured light technique (DAVID SLS-3, HP, Palo Alto, CA, USA) consisting of one projector and two cameras (Figure 1a). Then, the patients stood with their backs against and parallel to the wall with their shoulders touching the wall and their heads in the NHP. The front of the patient's head was optically scanned at a distance of about 1 m from the wall using the same scanner with the same conditions. This study was conducted in accordance with the Declaration of Helsinki and approved by the institutional review board (IRB) of Seoul National University Dental Hospital (CRI2017).

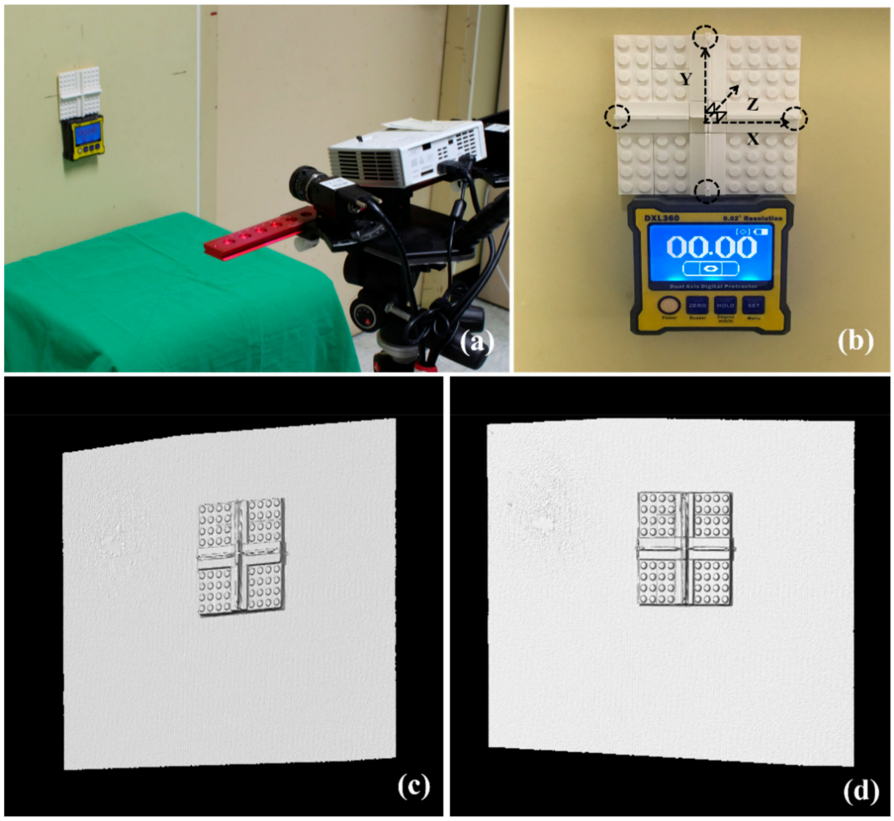


Figure 1. The calibration plate was attached to the wall parallel with the global horizon using a digital spirit level (**a**). The coordinate system of the calibration plate model was determined by the positions of four ceramic balls (indicated by the dashed circles) on the orthogonal cross of the calibration plate (**b**). The scanned model was positioned arbitrarily in the scanner coordinate system before calibration (**c**). The scanner coordinate system was aligned with the coordinate system of the calibration plate that was already oriented in the global horizon after calibration (**d**).

2.2. Immediate Calibration of the Scanner Coordinate System Using a Calibration Plate

We developed a calibration plate (80 × 80 mm in size) with four ceramic balls placed on an orthogonal cross using LEGO blocks (LEGO, LEGO, Billund, Denmark) in order to align the 3D optical scanner coordinate system with the CT coordinate system (Figure 1b). When the face of a patient was optically scanned, the coordinate system of the scanned model was commonly determined according to the arbitrarily positioned 3D optical scanner coordinate system. On the other hand, the CT scanner was typically positioned in the global coordinate system. Thus, we aligned the 3D optical scanner coordinate system with the global horizon by installing the calibration plate parallel with the global horizon. Then, the 3D optical scanner and CT coordinate systems coincided based on the global coordinate system. As a result, the calibration procedure was performed easily and immediately using the calibration plate.

To align the 3D optical scanner coordinate system with the global horizon, we used the four ceramic balls on the scanned model of the calibration plate as landmarks for setting the coordinate axes (the bottom, up, left, and right points on the orthogonal cross) (Figure 1b). The coordinate system ($\boldsymbol{P_C}$) of the calibration plate model was determined based on the 3D positions of the four landmarks extracted manually. The x-axis was defined from the left point to the right point, and y-axis from the bottom to the top. The z-axis was determined by calculating the cross product of the unit vectors for the two axes (Figure 1b). The scanner coordinate system ($\boldsymbol{P_S}$) was aligned with the global horizon by orienting ($\boldsymbol{P_G}$) it to the determined coordinate system of the calibration plate model that was already oriented in the global horizon (Equation (1)) (Figure 1c,d). Then, the coordinate system of the 3D scanned patient model could also be aligned with the global horizon by applying the same

orientation, as both the calibration plate and the patient were scanned (m_{s0}) by the same scanner under the same conditions (Equations (2) and (3)). As a result, we could acquire the 3D scanned patient head model in the NHP aligned with the global horizon (m_{s1}) by applying the resulting orientation to the patient model.

$$P_C = P_G P_S \tag{1}$$

$$m_{s1} = P_G m_{s0} \tag{2}$$

$$m_{s1} = P_C {P_S}^{-1} m_{s0} \tag{3}$$

where P_C is the calibration plate coordinate system, P_S, the scanner coordinate system, P_G, the rotation of the scanner, m_{s0}, the 3D scanned patient head model and m_{s1}, the 3D scanned patient head model oriented in NHP.

2.3. Automatic Reproduction of the 3D Patient NHP Model Using CPD Registration

We registered the patient's 3D CT head model (m_{c0}) with the optically scanned 3D head model in the NHP (m_{s1}) aligned with the global horizon using the surface registration method of a modified coherent point drift (CPD) algorithm, as described previously [16,17]. Registration based on the modified CPD was performed to minimize the distance between the patient's 3D CT head model and scanned 3D head model. The modified CPD consisted of two sequential registration steps. First, the coarse registration between the CT model and the scanned NHP model was performed using a principal component analysis (PCA) [16]. The centroid of the CT model was displaced into that of the scanned NHP model by applying the calculated translation, and the principal axes of the CT model were aligned with those of the scanned NHP model by applying the rotations calculated from the eigenvector matrix [16]. Then, the fine registration ($\mathbf{T}$) was performed using the CPD algorithm to match the two models more precisely [17]. After registration, the 3D NHP CT model (m_{c1}) could be reproduced automatically by applying the resulting transformation from the registrations to the patient CT model (Equation (4)).

$$m_{c1} = \mathbf{T}(m_{c0}) \tag{4}$$

where $\mathbf{T}$ is the transformation by the modified CPD algorithm, m_{c0}, the patient's 3D CT model, and m_{c1}, the reproduced patient's 3D CT model in the NHP.

2.4. Phantom Experiment

We used a mannequin phantom to evaluate the accuracy of the developed method. The whole procedure for recording and reproducing the NHP was as followed (Figure 2). The phantom was firmly mounted on a dedicated acrylic stand (Figure 3a). Then, four ceramic ball markers (1 mm diameter) were placed on the four corners of the top side of the acrylic stand base (Figure 3a). The marker positions were used to determine the true coordinate system of the phantom. The stand mounted by the phantom was bolted to a rotation stage with three degrees of freedom for controlling the rotation of the phantom (Figure 3a). Before CT scanning, we separated the rotation stage from the acrylic stand of the phantom. The phantom was arbitrarily positioned in the CT coordinate system during CT scanning.

The NHP recording procedure used for the phantom was the same as that used for the patients. First, we optically scanned the calibration plate installed parallel to the global horizon to the wall using a 3D scanner (Figure 1a). Then, the rotation stage, with three degrees of freedom, was again bolted to the acrylic stand of the phantom. We placed the rotation stage parallel to the wall and aligned the stage parallel with the global horizon using a digital spirit level. This made the coordinate system of the phantom parallel to the global horizon, and the phantom's posture was determined as the NHP of the phantom. The phantom in the NHP was optically scanned using the 3D scanner with the same conditions described previously (Figure 3b). Then, the coordinate system of the scanned phantom model was aligned with the global horizon using the orientation from the calibration plate. Finally,

the NHP rotation of the phantom's CT model was calculated by performing CPD registration between the phantom's CT head model and the optically scanned model.

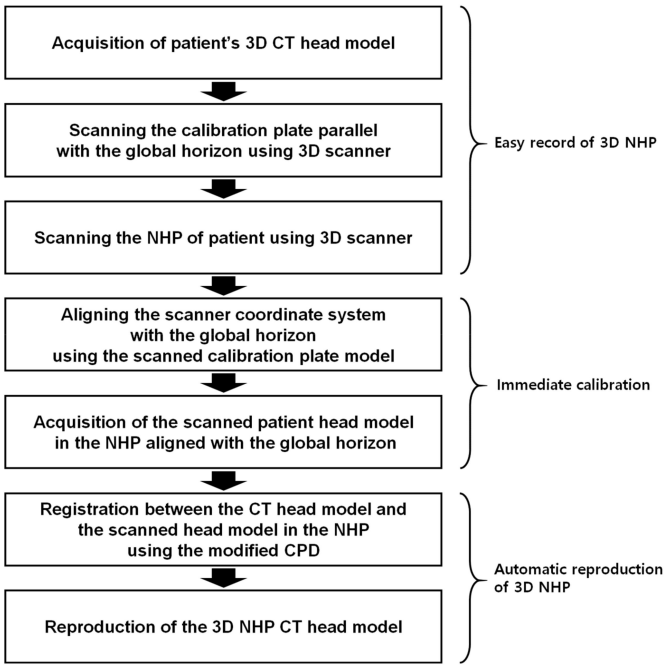


Figure 2. The whole procedure for recording and reproducing the NHP.

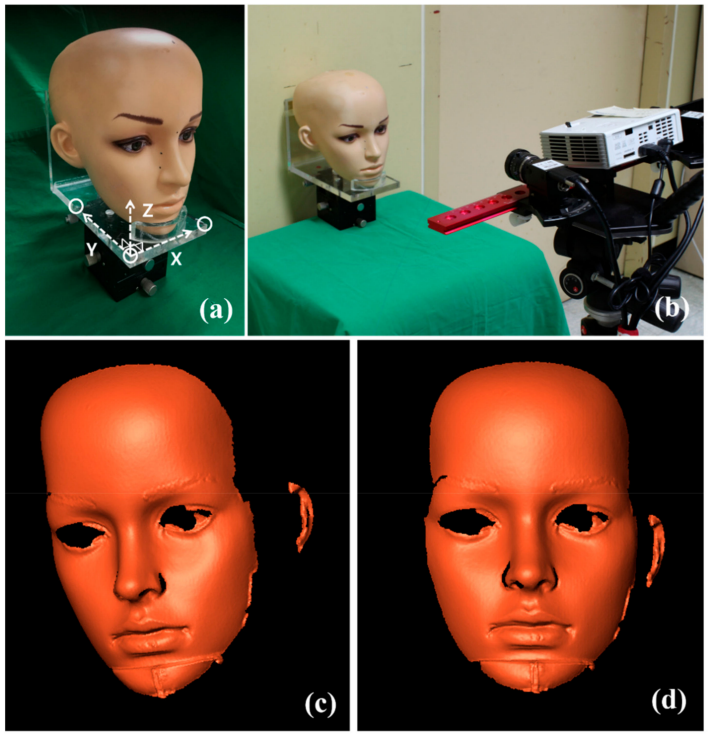


Figure 3. A mannequin phantom was mounted on an acrylic stand combined with a rotation stage, and the phantom's true coordinate system (indicated by the dashed arrow) was determined using ceramic spherical markers (indicated by the circle) placed on the acrylic stand (**a**). The phantom in the NHP was optically scanned using a 3D scanner (**b**). The 3D scanned phantom model shown before calibration (**c**), and the model aligned with the global horizon after calibration (**d**).

Optical scanning of the phantom was performed 15 times; CT scanning was performed only once and was used to calculate the phantom's NHP in all measurements without loss of generality. The true NHP of the phantom on CT imaging was determined based on the positions of the four ceramic markers placed on the acrylic stand base. The accuracy was calculated as the angle difference (°) between the true and calculated, as assessed by the developed method, orientations in the roll, pitch, and yaw directions.

For the evaluation of accuracy, a one–sample t-test was performed to determine whether the orientations obtained by the developed method were statistically different from the true orientations at a significance level of 0.05 (p-value). The data were statistically analyzed using SPSS (version 24, IBM, Armonk, NY, USA).

3. Results

A mannequin phantom was used to evaluate the accuracy of the developed method for recording and reproducing the NHP. The phantom CT data were obtained at an arbitrary position in the CT coordinate system. The calibration plate and the phantom were optically scanned sequentially using a 3D scanner. At that time, the phantom was set to be parallel to the global horizon, and this posture was defined as the NHP of the phantom. The coordinate system of the 3D scanned model was oriented to the global coordinate system immediately by applying the orientation information from the calibration plate. As a result, the scanned phantom model was also aligned with the global horizon by applying the same orientation as in the calibration (Figure 3c,d). Then, we automatically determined the transformation of the phantom CT model into the scanned NHP model by registration between the CT model and the NHP model using the modified CPD method (Figure 4). The deviation errors associated with the registration were expressed as color mapping (Figure 5). The mean deviation error was 0.26 ± 0.25 mm, and the positive and negative definite deviations were lower than one millimeter for most of the patients (Figure 5). We reproduced the phantom CT model in the NHP by applying the rotation from the registration to the CT model (Figure 6). For five patients with severe and mild facial asymmetries, we recorded the NHP of each patient once, and reproduced the patients' CT head model in the NHP using the same method (Figures 5 and 7).

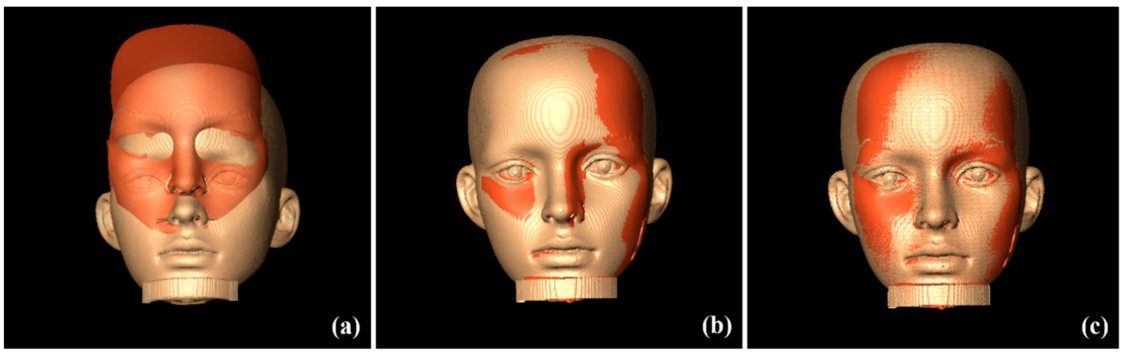


Figure 4. The phantom shown before rotation of the 3D CT model (in yellow) into the 3D calibrated scanned model (in red) (**a**), after rotation by coarse registration between the two models using a principal component analysis (PCA) (**b**), and after rotation by fine registration using CPD (**c**).

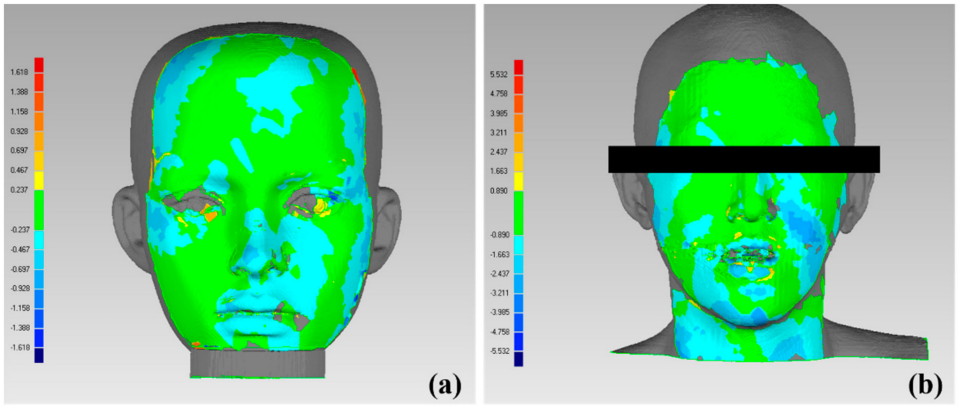


Figure 5. Three-dimensional registration error based on the modified CPD in the mannequin phantom (**a**) and in the patient (**b**).

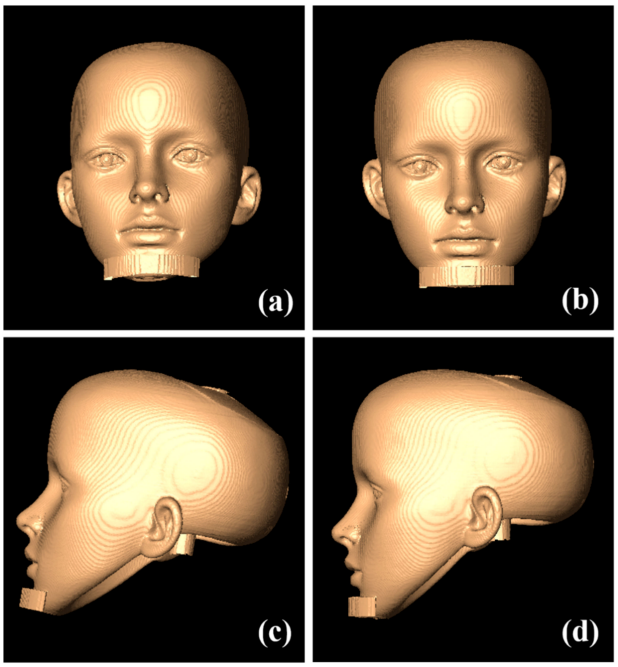


Figure 6. The phantom CT model shown before (**a**,**c**) and after (**b**,**d**) NHP rotation.

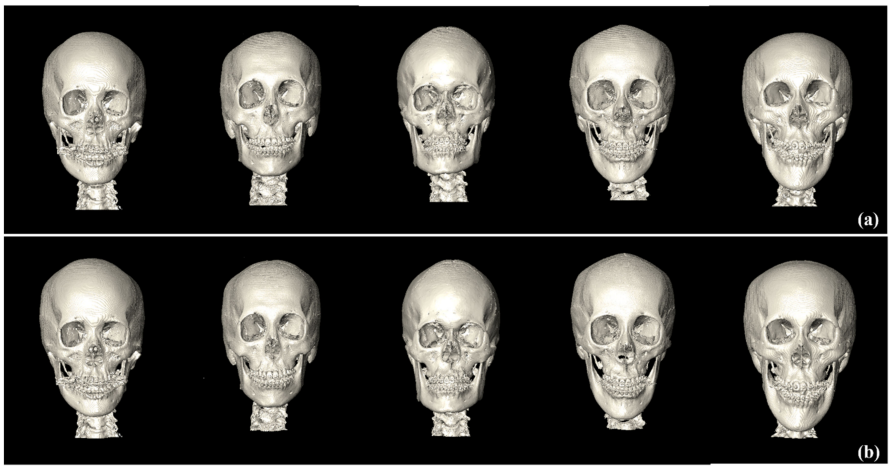


Figure 7. Patient CT head models shown before NHP reproduction (**a**) and after NHP reproduction (**b**) for patients with severe and mild facial asymmetries.

We evaluated the differences between true and calculated orientations in the roll, pitch, and yaw directions (Table 1). The mean angle differences were −0.05 ± 0.13°, 0.08 ± 0.22°, and −0.05 ± 0.18° in the roll, pitch and yaw directions, respectively, and the those of the worst case were −0.23°, 0.40°, and −0.32°. The measured roll, pitch, and yaw directions were not significantly different from the true directions assessed by one-sample *t*-tests ($p > 0.05$).

Table 1. The angle difference (°) between the true and calculated rotations in the roll, pitch, and yaw directions (mean ± SD).

Case	Roll (°)	Pitch (°)	Yaw (°)
1	−0.07	−0.04	−0.20
2	−0.23	0.40	−0.32
3	−0.07	0.08	−0.16
4	0.17	0.09	−0.04
5	0.11	0.42	−0.20
6	0.10	0.24	0.15
7	−0.09	0.12	0.16
8	0.08	0.42	−0.11
9	−0.06	0.04	−0.04
10	−0.07	−0.22	−0.09
11	−0.24	−0.09	−0.01
12	−0.27	0.10	0.26
13	−0.08	0.00	0.28
14	−0.07	−0.04	−0.20
15	−0.02	−0.30	−0.17
Mean	**−0.05 ± 0.13**	**0.08 ± 0.22**	**−0.05 ± 0.18**

4. Discussion

The natural head position (NHP) is the ideal reference position for assessing the facial morphology of patients with asymmetry [2,3]. Conventionally, many methods for recording and reproducing the NHP have concentrated on two-dimensional (2D) implementations using lateral cephalograms [4,5,7,18,19]. Recently, three-dimensional (3D) CT images have been widely used in the diagnosis and treatment of orthognathic patients [20–26]. However, the 3D CT head model does not represent the NHP, because the patient's head is located at an arbitrary position in the coordinate system during CT scanning. Therefore, there exists a growing need to reproduce 3D CT head models in the NHP.

There have been several studies investigating the 3D NHP reproduction of CT head models. In a previous study, we used a pose from orthography and scaling with iterations (POSIT) algorithm to orient 3D CT head models to the NHP using 2D images of the patient's face with spherical ceramic markers attached [9]. Although this method used a basic 2D digital camera, without the need for expensive equipment, and was able to preserve the patient's natural lip position in the 3D CT head model, manual extraction of the marker positions on the 3D CT model and the 2D image was time consuming, and attaching the fiducial markers to the face caused discomfort in the patients. Other studies have used 3D scanned head images obtained using a stereophotographic scanner system [13,14]. The method allowed automatic rotation of the 3D CT model to the 3D scanned patient model recorded in the NHP using surface registration [14]. However, the system was bulky and required a large space for recording the patient's NHP, and special devices, such as a reference board and a laser lever system, were necessary for calibrating the scanner coordinate system to a physical reference. Moreover, the calibration procedures required for using the devices were complex and time consuming for an inexperienced user.

We used a portable, structured light scanner to record the NHP of our patients. The structured light scanner uses patterns composed of line pairs to obtain 3D optically scanned images [27]. The scanner projects the patterns onto the object, and its camera captures the patterns. Then, the 3D points converted from the captured patterns are used to reconstruct the 3D model. The scanner used in this study does not require a large space to acquire a 3D scanned model compared with the space required for

a stereographic scanner system. Additionally, the scanner can be installed in a non-specific space unlike the stereographic scanner system [13,14]. In the stereographic scanner system, the calibration of the scanned image coordinate system to a physical reference was difficult and required much time and space, because the procedures using the reference board and the laser level system were complex [13,14]. In the present study, the calibration method using a calibration plate was easy to use and did not require much time or space. The calibration plate could be easily attached to the wall with its horizontal level adjusted to be parallel with the global horizon and scanned conveniently at an appropriate distance from the wall. Thus, calibration of the scanner coordinate system could be performed immediately using only the scanned model of the calibration plate. Moreover, as the calibration plate was small and portable compared with the reference board and laser level system used in other studies, the calibration method developed in our study did not require a specific space and could be also combined with other scanners.

We used 3D landmark points on an orthogonal cross across the calibration plate measured in the scanned model to align the scanner coordination system to the global horizon. Although the calibration and scanning procedures using the calibration plate were easy and convenient, the calibration accuracy may depend on the landmark positions manually measured on the plate. Manual measurement of landmark positions will cause inter- and intra-observer variations, which can decrease calibration accuracy and, eventually, the accuracy of the NHP reproduction. Thus, we used the average of several measurements of the landmark positions. To minimize inaccuracy, the automatic extraction of landmarks using image processing should eventually replace manual measurement.

We registered the patient's CT head model with their optically scanned head model in the NHP aligned with the global horizon using the surface registration method of a modified coherent point drift (CPD) algorithm [16,17]. The coarse registration between the CT model and the scanned NHP model was first performed using a principal component analysis (PCA) [16]. Then, fine registration was performed using the CPD algorithm to obtain a more precise match. The CPD considered the alignment of the two models as a probability density estimation, where one model represented the Gaussian mixture model (GMM) centroids, and the other represented the target of movements [17]. As the CPD uses a probability density estimation, such as a Gaussian mixture model (GMM), this probabilistic method performs better than the general iterative closest point (ICP) algorithm, which is commonly used for surface registration, especially in the presence of noise and outliers [17]. In this study, we automatically reproduced the 3D NHP CT model by applying the resulting transformation from the registrations to the patient's CT head model without manually selecting landmarks on the CT model for registration. Although the 3D CT head model was rotated to the NHP model semi-automatically by applying a pose from orthography and scaling with iterations (POSIT) algorithm [9], the method required time and labor to accurately extract the positions of the landmarks in the 3D CT head model and 2D image. Moreover, in the present study, there will be no intra- or inter-observer variation in accuracy of the NHP reproduction because NHP reproduction is performed automatically using the modified CPD registration. However, the positive and negative definite deviations for the patient's face were higher than those for the mannequin phantom when using the modified CPD registration. The registration error increased as human skin was more deformable. Nonetheless, the registration errors for most of the patient's face surface were lower than one millimeter.

The accuracy of the developed method for recording and reproducing the NHP model was −0.05 ± 0.13°, 0.08 ± 0.22°, and −0.05 ± 0.18° in the roll, pitch, and yaw directions, respectively. This accuracy was similar to those previously shown using the POSIT method: −0.04 ± 0.15°, −0.17 ± 0.50° and −0.02 ± 0.37° in the roll, pitch, and yaw directions, respectively [9]. The angular deviations using the stereophotogrammetry method were 0.2 ± 0.0778°, 0.2 ± 0.1042°, and 0.2 ± 0.0780° in the roll, pitch, and yaw directions, respectively [13]. Therefore, the accuracy and range of the present method is similar to those of previous studies using other scanning methods or photographs. Since the difference was less than 2°, our results were clinically acceptable and even the worst case was satisfactory [5]. However, the 3D images cannot be obtained by the structured light scanner system, and the accuracy

of this system can be lowered when the scanning field is too bright, as it is sensitive to illumination of the scanning field. Therefore, the structured light scanner is not recommended in a very bright environment to record the NHP of patients.

5. Conclusions

In this study, we developed a new method for easily recording and automatically reproducing 3D NHP models based on immediate calibration using a portable 3D scanner and a calibration plate. The calibration for aligning the scanner coordinate system with the global horizon could be performed easily by an inexperienced user, and the 3D NHP model could be reproduced automatically using the modified CPD algorithm. Further, the accuracy of the developed method was high enough to be acceptable for clinical use. Therefore, we expect the developed method can be used for diagnosing and treating orthognathic patients with facial asymmetry more accurately and conveniently than the currently availably methods. In future studies, we hope that this method is able to work across genders, race, ethnicity, etc. with more patients, and to develop a method for the reproduction of the patient's NHP involving eliminating the recording process using artificial intelligence.

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Conflicts of Interest: The authors declare no conflict of interest.

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