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The difference between registered natural head position and estimated natural head position in three dimensions.

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Short running title: Registered natural head position and estimated natural head position in 3D.

Key words: Estimated natural head position; registered natural head position; natural head position; Class III; orthognathic surgery

Abstract

This study determined the intra-rater repeatability and inter-rater reproducibility of re-orientating three-dimensional (3D) facial images into estimated natural head position. Three-dimensional facial images of 15 pre-surgical Class III orthognathic patients were obtained and automatically reoriented into natural head position (RNHP) using a 3D stereophotogrammetry system and in-house software. 6 clinicians were asked to estimate the natural head position of these patients (ENHP); they re-estimated 5 randomly selected 3D images after a 2-week interval. The differences in yaw, roll, pitch and chin position between RNHP and ENHP were measured. For intra-rater repeatability the intra-class coefficient (ICC) values ranged from 0.55 to 0.74 representing moderate reliability for roll, yaw, pitch and chin position, whilst for inter-rater reproducibility ICC values from 0.39 to 0.58 indicated poor to moderate reliability. Median differences between ENHP and RNHP was small for roll and yaw but larger for pitch. There was a tendency for the clinicians to estimate NHP with the chin tipped more posteriorly (6.3±5.2mm) compared to RNHP; reducing the severity of the skeletal deformity in the anterior-posterior direction.

Keywords: Estimated natural head position; registered natural head position; natural head position; Class III; orthognathic surgery

Introduction

Head orientation influences the anterior-posterior perception of the maxillo-mandibular complex and may result in incorrect diagnosis.[1,2] Currently intracranial reference lines such as Frankfort Horizontal (FH) and sella-nasion (SN) are widely used in standardising lateral head film orientation. [3,4] Natural head position (NHP) is more reproducible and is an alternative method of recording head orientation.[5-7] As a consequence NHP has gained popularity with both orthodontists and oral and maxillofacial surgeons.[8] NHP is readily retrievable from a profile photograph or lateral cephalogram by using a true vertical reference line and is referred to as "registered natural head position".[9]

Three-dimensional (3D) surface imaging has become a routine method of capturing pre-treatment facial images. The calibration of the device does not usually consider any physical reference lines or planes and only the patients' surface topography irrespective of orientation is captured.[10] Even though the patients' facial image is captured in NHP, the resulting 3D facial image when re-loaded into viewing software, will be displayed in an orientation dictated by the calibration and will no longer be in the correct orientation, Figure 1 and 2. To overcome this problem the concept of "registered natural head position" (RNHP) was suggested.[9] RNHP uses devices which record and transfer NHP, these include registration jigs[11], digital orientation sensors[12] and a laser level beam.[13-15] However the devices themselves may influence the accuracy of RNHP and in some cases cause soft tissue distortion. Hsung et al. (2014) proposed the use a "physical reference system", based on a secondary reference target, to re-orient the captured images to the pose the individual were originally captured, e.g. NHP. This technique was accurate and could be regarded as a method (gold standard) of re-orientating 3D facial images into NHP.[10]

In situations where lateral cephalograms or lateral profile photographs are not taken in NHP it is possible for clinicians to re-orientate the profile image (up and down) into “estimated natural head position” (ENHP).[16,17] For 3D images the complexity increases as the images can be manipulated with six degrees of freedom, three for changes in position (translation) along the *x*, *y*, and *z* axes, in addition to rotation around each of the three axis. The majority of 3D virtual orthognathic planning software packages requires the user to load and re-orient the 3D image into the correct pre-planning position i.e. NHP. The assumption is that this can be carried out correctly based on subjective clinical estimation or the use of some form of positioning device.

Given that 3D images are not always displayed in NHP and positioning devices are not routinely available, the purpose of this study was to determine the intra-rater repeatability and the inter-rater reproducibility of re-orientating 3D facial images, of a group of Class III patients, into estimated natural head position (ENHP). The primary outcome measure was the difference in chin position between the ENHP and RNHP orientation using the technique suggested by Hsung et al. (2014). The null hypothesis was that the difference in anterior-posterior chin position (z direction) between the ENHP and RNHP orientation was not different to 6mm as this has been found to be clinically significant.[18]

Materials and methods

Sample size calculation

Based on a standard deviation of 3.5° in the sella-nasion line to horizontal plane (S-N/HOR) angle between RNHP and ENHP[19], an SN length of approximately 6.5cm[20], SN-Pog angle of approximately 80 degrees[21] and total anterior face height of 116mm[20] the corresponding standard deviation at the chin (pogonion) would be expected to be approximately 5mm. Using Minitab 17 (Minitab, State College, PA) it was calculated that with 90% power, a significance level of 0.05 and a 6mm clinical significance[18] a minimum sample size of 10 Class III orthognathic surgical patients would be needed.

Patient recruitment

Following ethical approval by the Institutional Review Board (IRB) of Hong Kong University and Hospital Authority Hong Kong West Cluster (Protocol reference no: UW 14-355), patients seeking treatment at the Department of Orthodontics or the Department of Oral Maxillofacial Surgery at the Prince Philip Dental Hospital were recruited. Based on the diagnosis of the orthognathic team only pre-surgical Class III orthognathic patients with no facial asymmetry were included. Individuals with craniofacial syndromes or anomalies were excluded. The average age of 15 of the patients was 21.9 years ± 8.5 months (range 17.2–26.9 years); 12 were female and 3 male.

Clinicians

Six experienced clinicians (four males and two females; age range: 27–34 years) from the Department of Orthodontics and the Department of Oral Maxillofacial Surgery, who were familiar with and routinely used, natural head position were asked to estimate natural head position, by adjusting the pitch, roll and yaw orientation of the image, Figure 3.

3D imaging system calibration

A 3D stereophotogrammetry system (Di3D, Dimensional Imaging, Glasgow, UK) was adapted to record registered RNHP[10] and capture the 3D facial image of each of the subjects. According to the method there were three steps; firstly, the position of mirror (25 cm x 21 cm) was recorded in three planes of space. Secondly, the intrinsic properties of the Di3D system were calibrated using Di3D calibration target. Finally, the physical external references were determined by aligning reference board parallel to the mirror.

Obtaining registered natural head position (RNHP)

Subjects were asked to cover their hair with a headband and remove their glasses prior to 3D facial captures. They were then seated in front of the 3D capture system and instructed to obtain NHP as follows: sit upright, close their left eye and use their right eye to focus on a black point on the mirror and adjust the seating position if necessary, tilt their head forward and backward with decreasing oscillations until a comfortable position of the head was obtained.[22] Finally look into their own eyes in the mirror and in relaxed lip position. When the subjects were in NHP, 3D facial captures were obtained using Di3Dcapture software (Dimensional Imaging, Glasgow, UK). All captures (at least five captures) were exported in Wavefront (OBJ) format and using the appropriate in-house software all subsequent 3D facial captures were automatically reoriented into RNHP (HTC).

Obtaining estimated natural head position (ENHP)

The 3D images in RNHP were first imported to MeshLab software (STI-CNR, Rome, Italy; http://meshlab.sourceforge.net/) and each image was prepared for standardised viewing by deleting the shoulders and hair but leaving the ears and neck region. The pitch, roll and yaw of each cropped 3D images was then changed using MeshLab. The amount of change was a figure from 10° to 30° generated by a random number generator. The image was then saved as a new .OBJ file. Each 3D image, in its new orientation, was imported into Di3Dview installed on a Dell PC computer (Dell precision T5600, Dell Inc., Texas, US) with a 24" LED wide screen monitor. To familiarize the clinicians with the software, a demonstration was conducted prior to the main study. The clinicians were shown how to change the pitch, roll and yaw of the image. For the main study the clinicians were asked to re-orientate each 3D images into natural head position based on their general experience with no time limitation (T1). Each image was saved in the new position in OBJ format.

To assess the intra-operator reliability five randomly selected RNHP images were re-orientated into ENHP by 6 clinicians after a 2-week interval (T2). It has been reported that two weeks is an acceptable washout interval.[23] For each patient the RNHP and ENHP image were imported into Di3Dview. A single landmark was placed at pronasale on both images. The ENHP image was translated long the mediolateral direction (x axis), inferosuperior direction (y-axis) and anteroposterior direction (z-axis) and aligned on pronasale, which then served as the center of rotation and the local co-ordinate system. The aligned ENHP image was saved in OBJ format. Using in-house developed software three soft-tissue landmarks were selected on the RNHP which displayed the vertex number associated with the landmark, Figure 4. As the RNHP and the ENHP were the same image the same vertices could be identified on the ENHP. It is more meaningful to consider the three landmarks as a triangle undergoing rigid body transformation, Figure 5.

Determining the differences in yaw, roll and pitch between ENHP and RNHP

To determine the differences in yaw the angle between the lines joining the left exocanthian and the right exocanthian on both the ENHP and RNHP images of each participant was measured as if they were projected on the X-Z plane, Figure 6. The error in roll was determined by projecting the same lines on the X-Y plane, Figure 7. Finally the difference in pitch was calculated by measuring the angle between the lines joining pronasle and pogonion on both the ENHP and RNHP images as if they were projected on the Y-Z plane, Figure 8. The angle (θ) between two lines is measured by the equation $\theta = \cos^{-1}\left(\frac{\boldsymbol{a}\cdot \boldsymbol{b}}{|\boldsymbol{a}||\boldsymbol{b}|}\right)$, where **a** and **b** are the vectors pointing in the direction of each line.[24]

Statistical analysis

The mean differences in x, y and z coordinates of the three landmarks between RNHP and ENHP were measured and descriptive statistics determined. The data was checked for outliers and normality. No outliers were found and the differences between the x, y and z co-ordinates for the RNHP and ENHP images were found to be normally distributed. Therefore a one-sample *t*-test was performed to detect whether the difference in chin position in the z direction (pitch) was significantly different to 6mm.

An intra-class coefficient (ICC) analysis was used to assess the intra-rater (one-way random) and inter-rater repeatability (two-way mixed) for roll, yaw, pitch and chin position for the six clinicians. ICC values of 0.75 and above represent good reliability, those between 0.50 and 0.74 represent moderate reliability, and those below 0.50 indicate poor reliability.[25]

Results

The mean differences in the x direction were 0.0±1.1mm, -0.3±1.2mm and 0.4±1.7mm for the right eye, left eye and chin respectively. The mean differences in the y direction were 2.9±2.6mm, -2.3±2.7mm and -1.2±1.4mm for the right eye, left eye and chin respectively. Finally the mean differences in the z co-ordinate were -4.0±3.5mm, -2.7±2.9mm and 6.3±5.2mm for the right eye, left eye and chin respectively, Table 1. The results of the one-sample *t*-test showed that the mean difference in chin position, in the z direction, between ENHP and RNHP was 6.3±5.2mm and not significantly different to 6mm (p=0.645), with a 95% confidence interval of 5.2mm to 7.3mm.

Figure 9 shows there was a tendency for the clinicians to orientate the ENHP image so the chin was rotated more posteriorly (6.3±5.2mm) in the z direction. As expected with the chin more posterior placed the right and left eyes (4.0±3.5mm and -2.7±2.9mm) were more anteriorly positioned as the images were centred and rotated around pronasale.

Intra-operator reliability

For intra-operator reliability the ICC values of 0.55 to 0.74 represent moderate reliability for roll, yaw and pitch. Median differences between ENHP and RNHP for roll (-0.3^{o}) and yaw (0.2^{o}) were small but were larger for pitch (-1.3^{o}), Table 2.

Inter-rater reproducibility

The ICC values ranged from 0.39 to 0.58 represent poor to moderate reliability for roll, yaw and pitch between clinicians. Median differences between ENHP and RNHP for roll (-0.7^{o}) and yaw (-0.2^{o}) were again small but much larger for pitch (5.5^{o}), Table 3.

Discussion

The fundamental premise of assessment, diagnosis and treatment planning for individuals with a dentofacial deformity relies on correct head positioning (Downs, 1956). Based on conventional 2D facial photographs natural head orientation (NHO) or estimated natural head position (ENHP) is an alternative to registered natural head position (RNHP).[19,23] To the authors knowledge there are no equivalent studies using 3D facial images. The ability to correctly re-orientate a 3D facial image into the correct

NHP is the starting point of virtual orthognathic surgical planning. This study was undertaken to determine the validity and reproducibility of undertaking this fundamental process based on subjective estimation only.

Ideally natural head position should be recorded without any devices attached to the head, any markings on the face, or the use of subjective datum points.[9] "Stereophotogrammetric natural head position" developed by Hsung et al. (2014) attains these requirements. Even though the method may not be readily usable in a clinical setting it did provide the "gold standard" to obtain RNHP for the present study. The repeatablity of the physical reference system was clinically acceptable, with standard deviations less than 0.1° for pitch and yaw angles and 0.15° for roll angles.

The moderate level of intra-operator reliability for roll, yaw and pitch indicates that individual clinicians could estimate natural head position consistently in three-dimensional space. The median differences between ENHP and RNHP for roll (-0.3°) and yaw (0.2°) were small but were larger for pitch (-1.3°). It is worth noting the 95% confidence interval for difference in chin position in the z direction (5.2mm to 7.3mm), may have the potential to alter clinical assessment and outcome.

The poor to moderate inter-operator reliability indicated that 3D facial images could be reliably orientated into natural head position with respect to roll and yaw only but not pitch. The smaller differences in roll and yaw for both intra- and inter-operator reliability may be explained by clinicians using the eyes (pupils) to orientate the image horizontally and reducing roll error. The clinicians may also be using the ears and the "amount of cheek show" on the left and right halves of the facial image to adjust for rotational symmetry, therefore reducing yaw error. This hypothesis could be tested by repeating the study on a group of patients with hemifacial macrosomia. The orbital dystopia, differences in ear height and in asymmetric hemifacial projection may have a marked effect on the roll and yaw as well as the pitch; this was beyond the scope of the present study. Regarding pitch estimation there are few visual cues to guide the clinician which may explain the difficulties in reaching a consensus on the pitch orientation and so chin position. In the absence of such visual cues clinicians maybe using their own references for pitch, i.e. Frankfort plane. However, similar with the cephalometric radiographs, difficulties in locating soft-tissue landmarks accurately on a 3D image may result in the differences amongst clinicians.

The present study has found that clinicians overwhelmingly orientated a 3D facial image so that the chin lies more posteriorly when estimating NHP with a mean difference of 6.3±5.2mm (95% confidence interval of 5.2mm to 7.3mm). Interestingly this was agreement with a previous study using 2D images to assess whether NHO is influenced by facial morphology. The study reported the severity of both class II and class III skeletal patterns were underestimated.[17]

The effect of chin position on the perceived need for orthognathic surgery has been previously reported.[26] The study reported that when chin prominence reached approximately 6mm beyond a class I acceptable profile surgery was suggested by laypeople, orthognathic patients and clinicians. Interestingly, in the present study, the difference between ENHP and RNHP chin position in the z direction was not significantly different to 6.0mm (p=0.645); this would imply a clinically acceptable result. However, it should be noted that the chin prominence was compared starting from a class I profile whilst the present study starts with skeletal class III patients. This difference may exaggerate the severity of chin prominence and still has the possibility to change the desire for surgical correction amongst clinicians. Also the range of error for pitch was large, from -3.5^{o} upto 13.2^{o}, again highlighting the inconsistency in re-orienting the image correctly.

In conclusion, many current 3D imaging techniques do not maintain the recorded natural head position. This study has shown that subjective re-orientation of 3D images into NHP is reproducible with respect of roll and yaw, in the absence of facial asymmetry, but not in pitch. The subjective re-orientation of 3D images into NHP in class III patients may reduce the perceived severity of the skeletal deformity in the anterior-posterior direction i.e. they will look less class III. Therefore when using 3D virtual planning clinicians require an additional frame of reference to orientate the images prior to planning, as clinicians are unable to re-establish the correct NHP reliably.

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The authors would like to thank the clinicians for their time and support in conducting this study and the staff of the Orthodontic and Oral and Maxillofacial Discipline for patient recruitment.

Declarations

Funding: None

Competing Interests: None

Ethical Approval: Ethical approval was granted by the Institutional Review Board (IRB) of Hong Kong University and Hospital Authority Hong Kong West Cluster (Protocol reference no: UW 14-355).

Patient Consent: Written patient consent has been obtained to publish clinical photographs.

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Tables

Table 1 Descriptive statistics showing the mean differences in x, y and z coordinates of the three landmarks between RNHP and ENHP.

Table 2 Intra-rater reliability for roll, yaw, pitch and chin position. Also shown are the median differeances, range and interquatile range between RNHP and ENHP for roll, yaw and pitch.

Table 3 Inter-rater reliability for roll, yaw, pitch and chin position. Also shown are the median differeances, range and interquatile range between RNHP and ENHP for roll, yaw and pitch.

Figures

Figure 1 Simultaneous 2D and 3D capture. Subject captured in NHP based on true vertical line in 2D.

Figure 2 Subject image captured once, but reloaded and viewed based on three different calibration target orientations. Note change in head position.

Figure 3 Shows the co-ordinate system used in this study and the pitch, yaw and roll rotations around the x, y and z axis respectively.

Figure 4 3D image showing landmarks used during analysis - right exocanthion (landmark 1), left exocanthion (landmark 2), pogonion (landmark 3) and centre of rotation (landmark 4).

Figure 5 3D landmark configuration simplified to a triangle RNHP (yellow) and ENHP (red) with center of rotation on pronasale.

Figure 6 Roll angle calculated between right exocanthion (landmark 1), and left exocanthion (landmark 2) joined on both RNHP (yellow) and ENHP (red) images and projected onto the coronal (X-Y plane) looking down the z-axis (Gateno, 2011).

Figure 7 Yaw angle calculated between right exocanthion (landmark 1), and left exocanthion (landmark 2) joined on both RNHP (yellow) and ENHP (red) images and projected onto the axial (X-Z plane) looking down the y-axis (Gateno, 2011).

Figure 8 Pitch angle calculated between pronasale (landmark 4), and pogonion (landmark 3) joined on both RNHP (yellow) and ENHP (red) images and projected onto the sagittal plane (Y-Z plane) looking down the x-axis (Gateno, 2011).

Figure 9 Distribution showing the frequency of ENHP 3D facial image orientated so that the chin lies more posteriorly (-ve) or anteriorly (+ve) than the RNHP.

Acknowledgments

The authors would like to thank the clinicians for their time and support in conducting this study and the staff of the Orthodontic and Oral and Maxillofacial Discipline for patient recruitment.

Declarations

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Tables

Table 1 Descriptive statistics showing the mean differences in x, y and z coordinates of the three landmarks between RNHP and ENHP.

	Mean difference (mm)	SD (mm)	95% CI for mean difference (mm)	
			Lower	Upper
Right eye				
x	0.0	1.1	-0.2	0.2
y	-2.9	2.6	-3.5	-2.4
z	-4.0	3.5	-4.8	-3-3
Left eye				
x	-0.3	1.2	-0.3	0.2
y	-2.3	2.7	-2.9	-1.7
z	-2.7	2.9	-3.3	-2.1
Chin				
x	0.4	1.7	0.1	0.7
y	-1.2	1.4	-1.5	-0.9
z	6.3	5.2	5.2	7.3

Mean difference = (RNHP – ENHP).
Positive (+) values in the x, y and z directions indicate the ENHP image is to the left, lower and more posterior compared to the RNHP image respectively.

Table 2 Intra-rater reliability for roll, yaw, pitch and chin position. Also shown are the median differeances, range and interquatile range between RNHP and ENHP for roll, yaw and pitch.

	ICC	95% CI for ICC	Median difference (degrees)	Minimum (degrees)	Maximum (degrees)	Interquartile range (degrees)
Roll	0.55	0.24 to 0.75	-0.3	-2.9	1.4	1.5
Yaw	0.64	0.37 to 0.81	0.2	-5.9	2.9	1.3
Pitch	0.74	0.53 to 0.87	-1.3	-6.2	7.9	3.1

Table 3 Inter-rater reliability for roll, yaw, pitch and chin position. Also shown are the median differeances, range and interquatile range between RNHP and ENHP for roll, yaw and pitch.

	ICC	95% CI for ICC	Median difference (degrees)	Minimum (degrees)	Maximum (degrees)	Inter-quartile range (degrees)
Roll	0.39	0.18 to 0.66	-0.7	-3.1	3.2	1.8
Yaw	0.58	0.31 to 0.76	-0.2	-3.9	5.3	3.0
Pitch	0.39	0.19 to 0.66	5.5	-3.5	13.2	7.3

Figure 1
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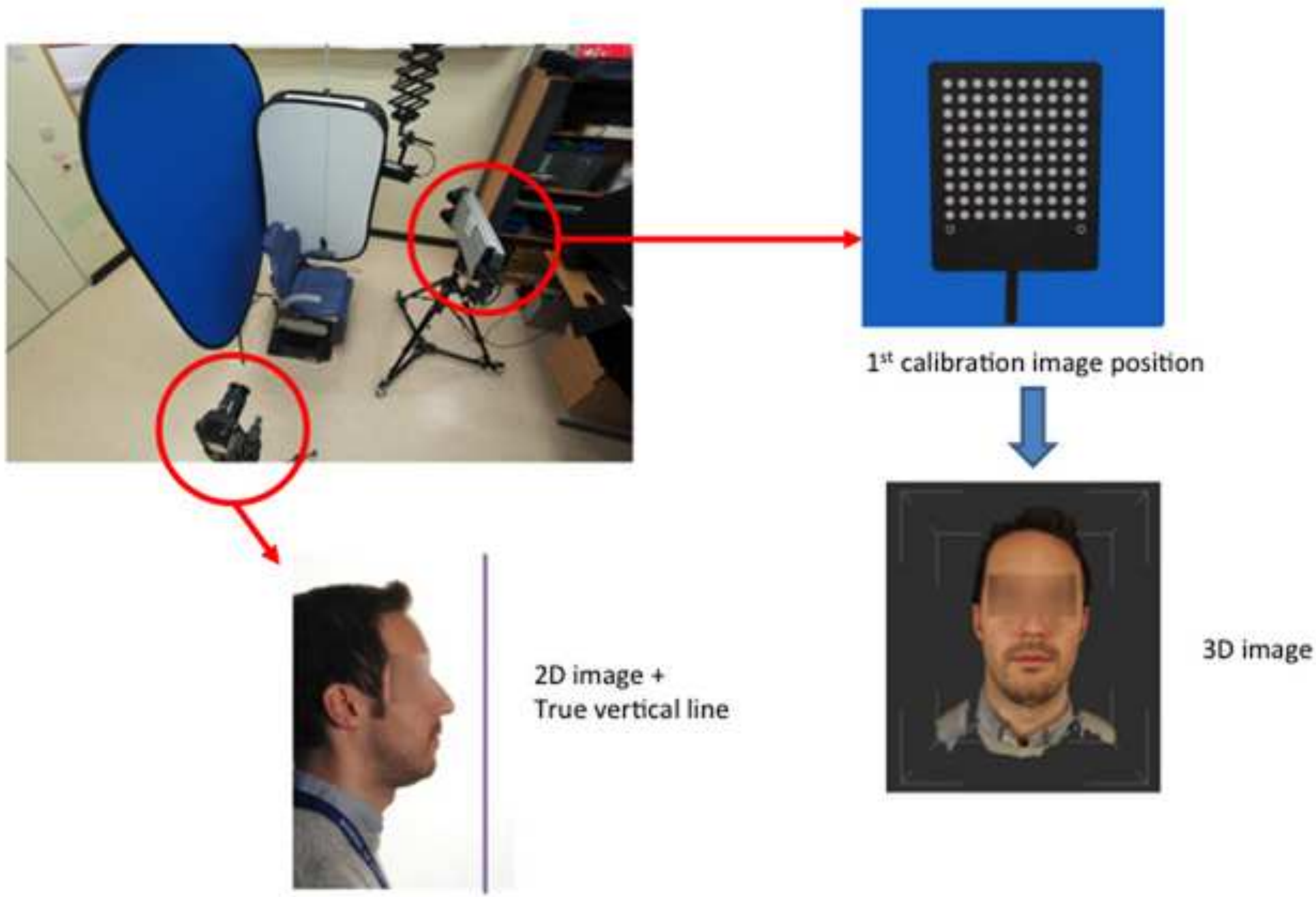

Figure 2

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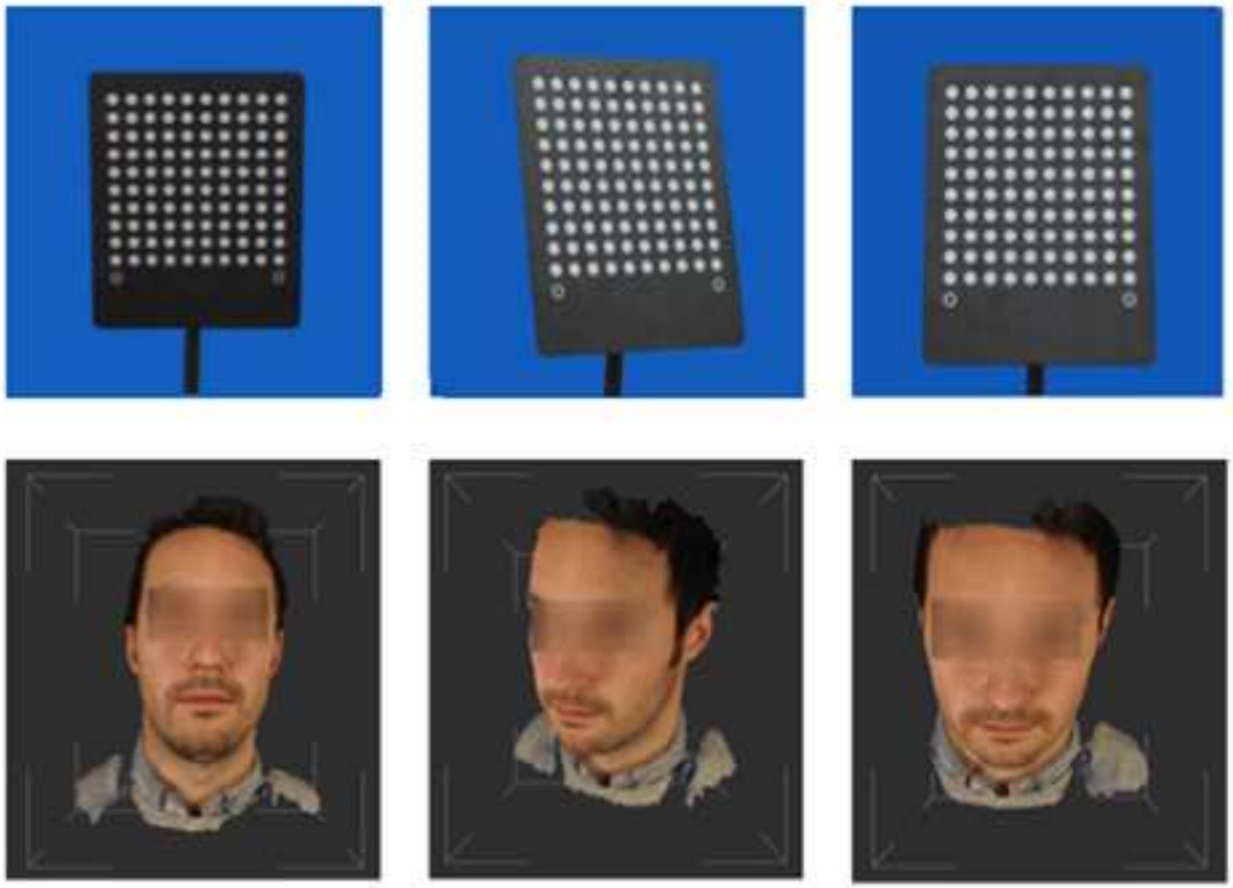

(a) (b) (c)

Figure 3
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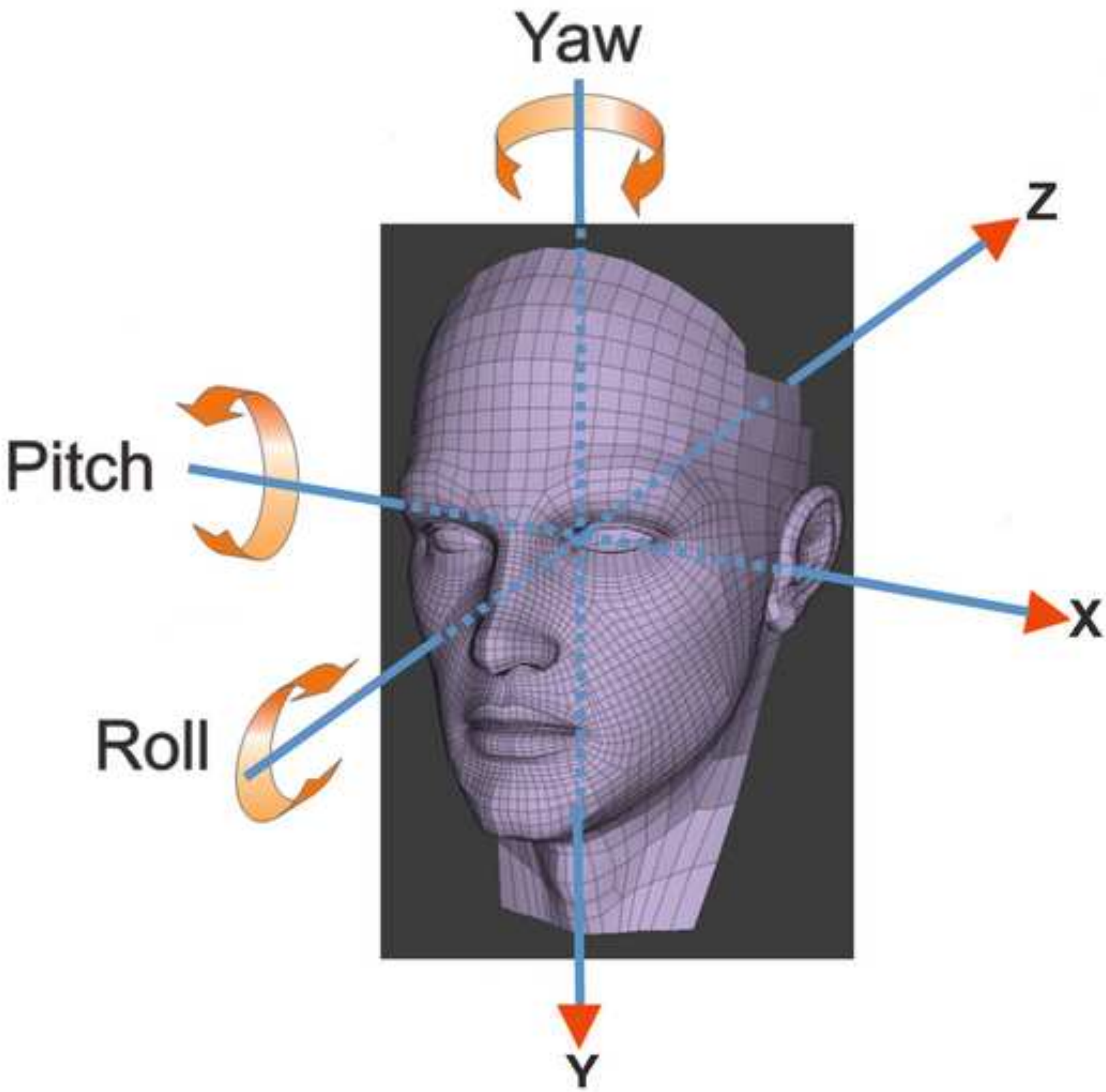

Figure 4

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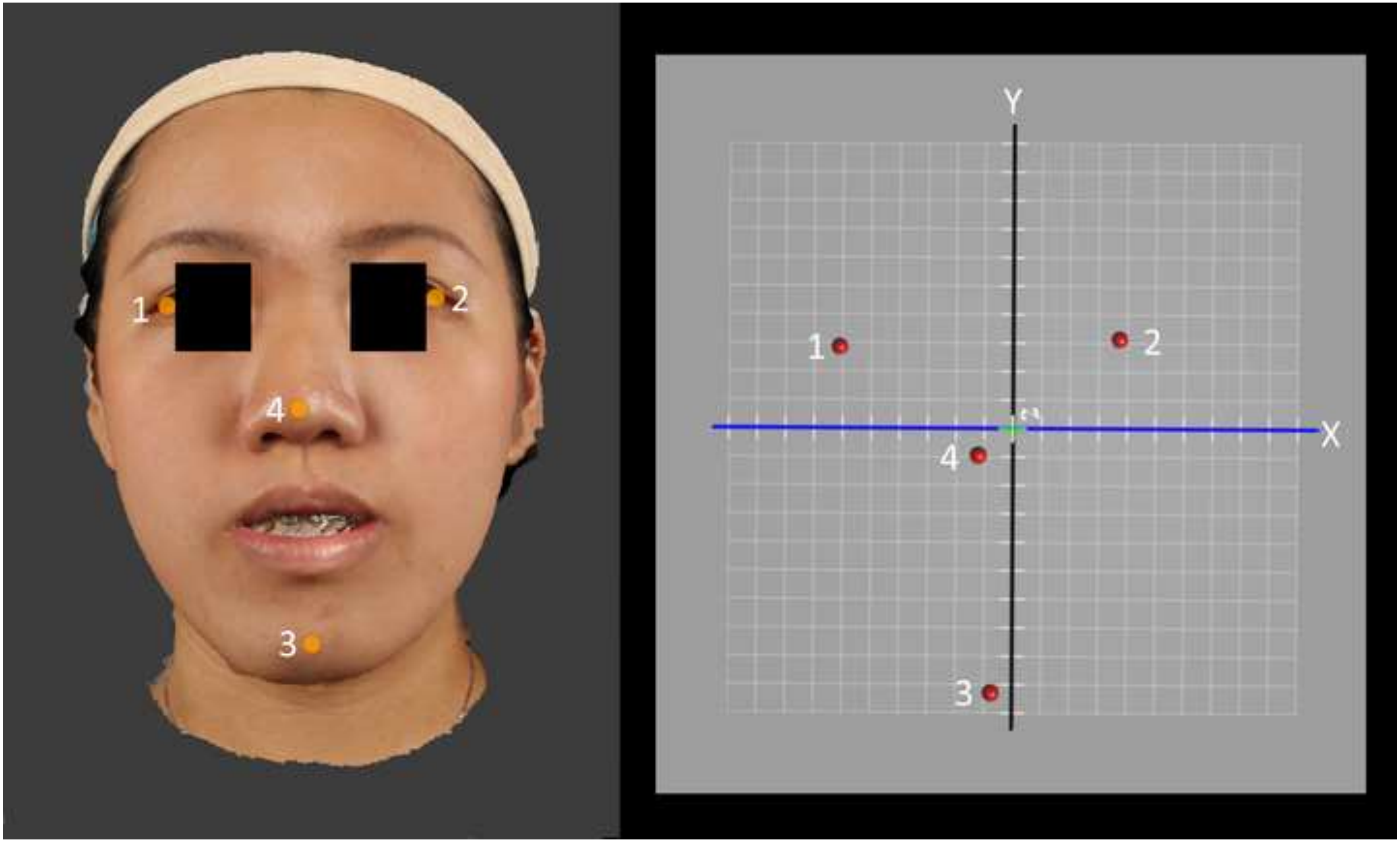

Figure 5

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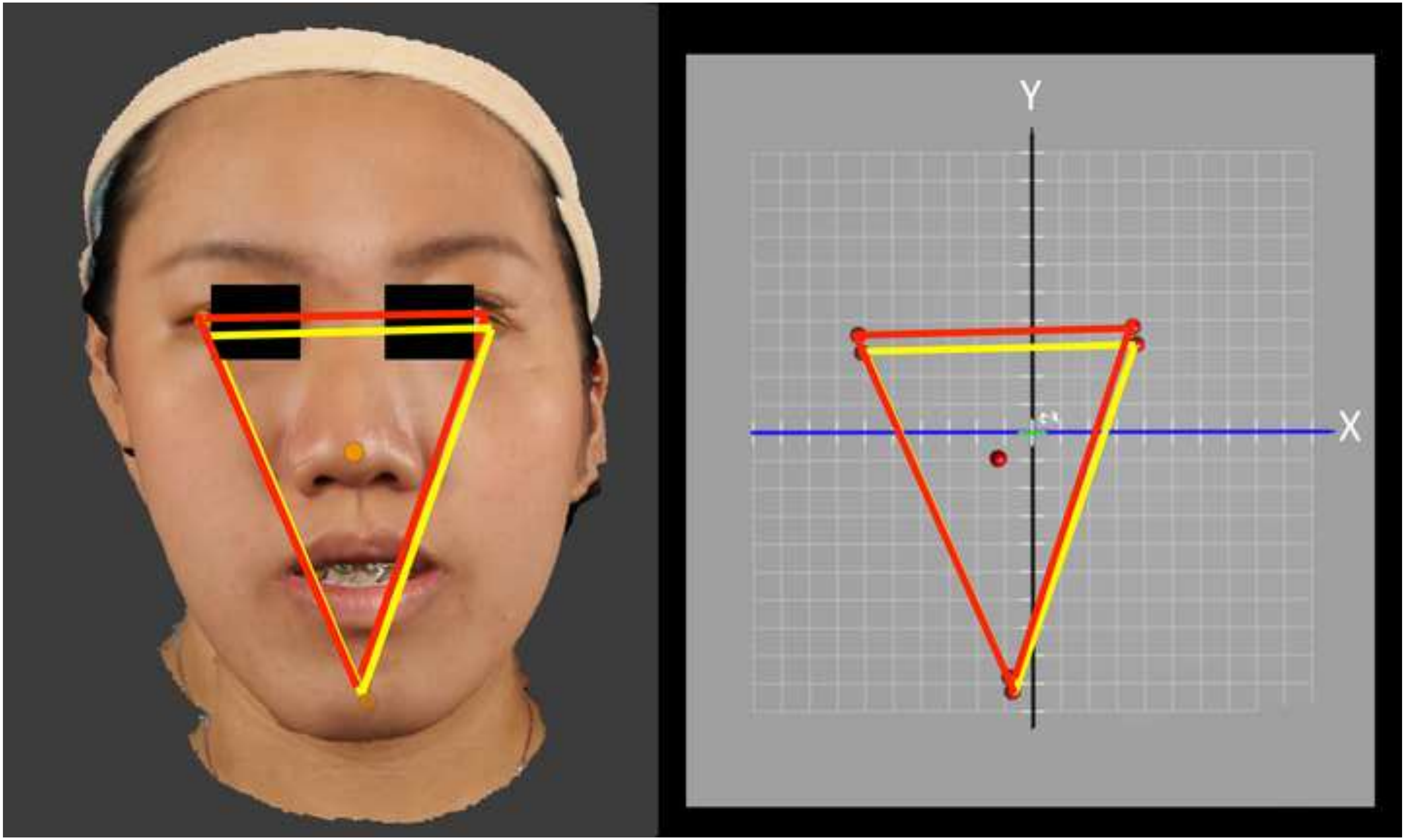

Figure 6
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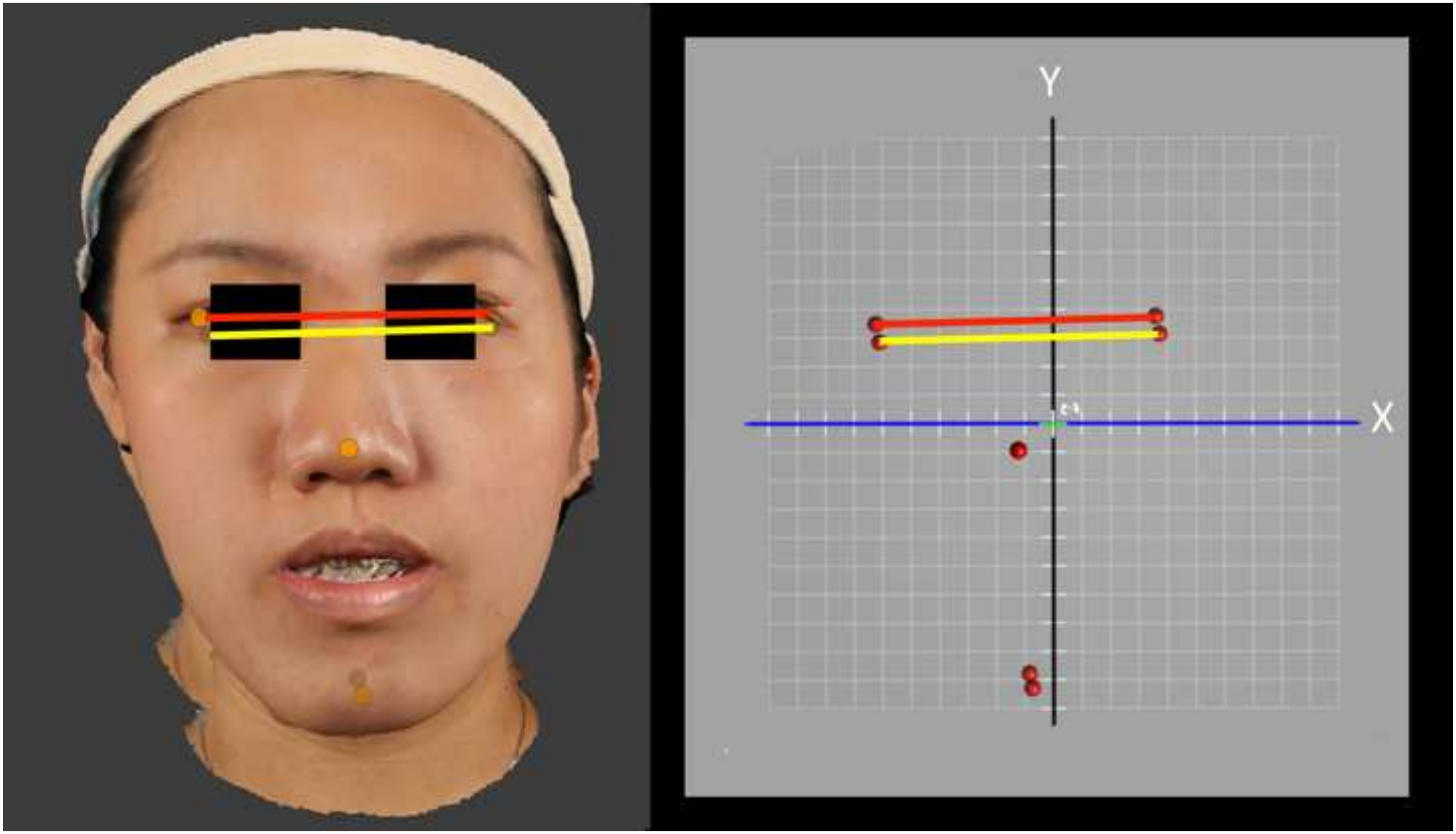

Figure 7
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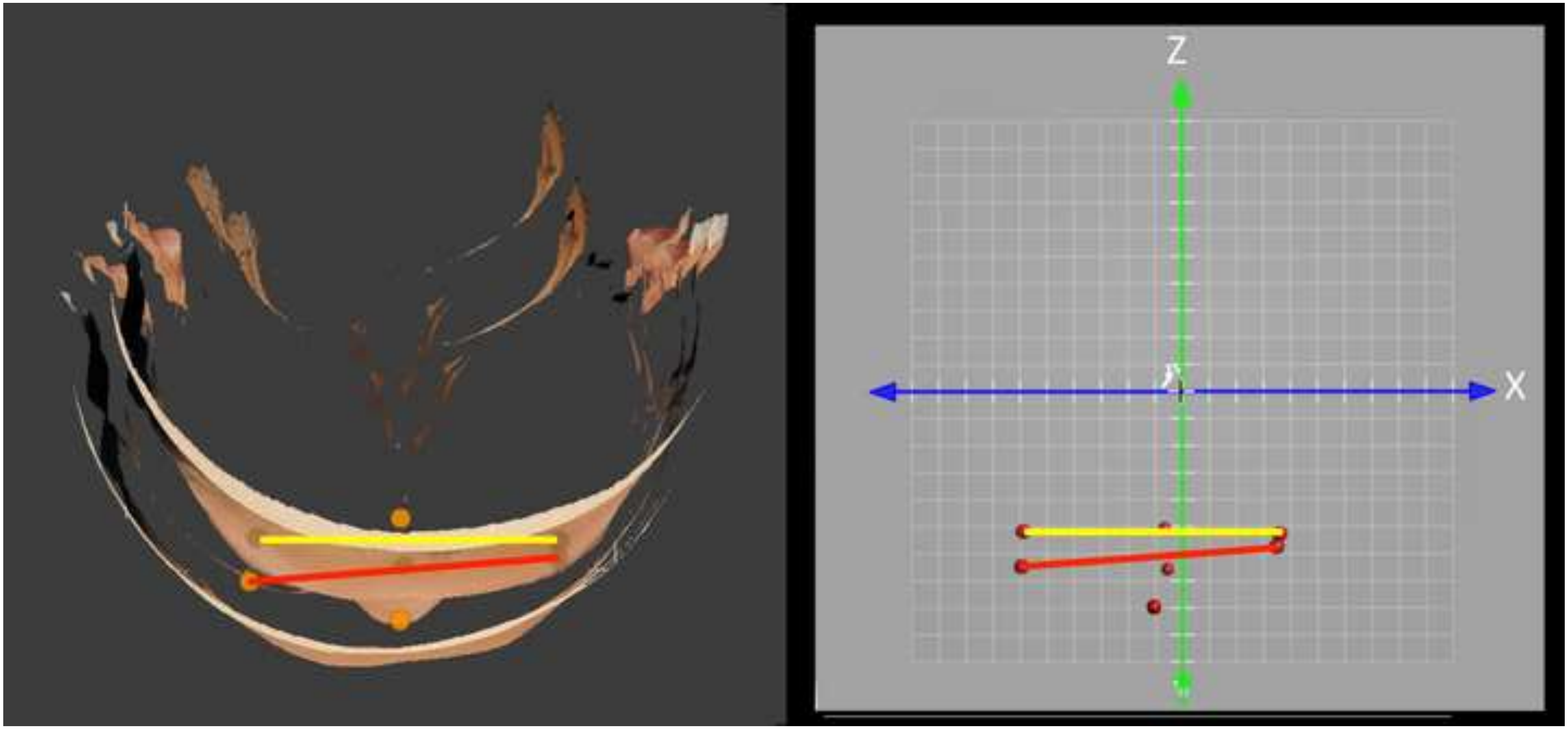

Figure 8
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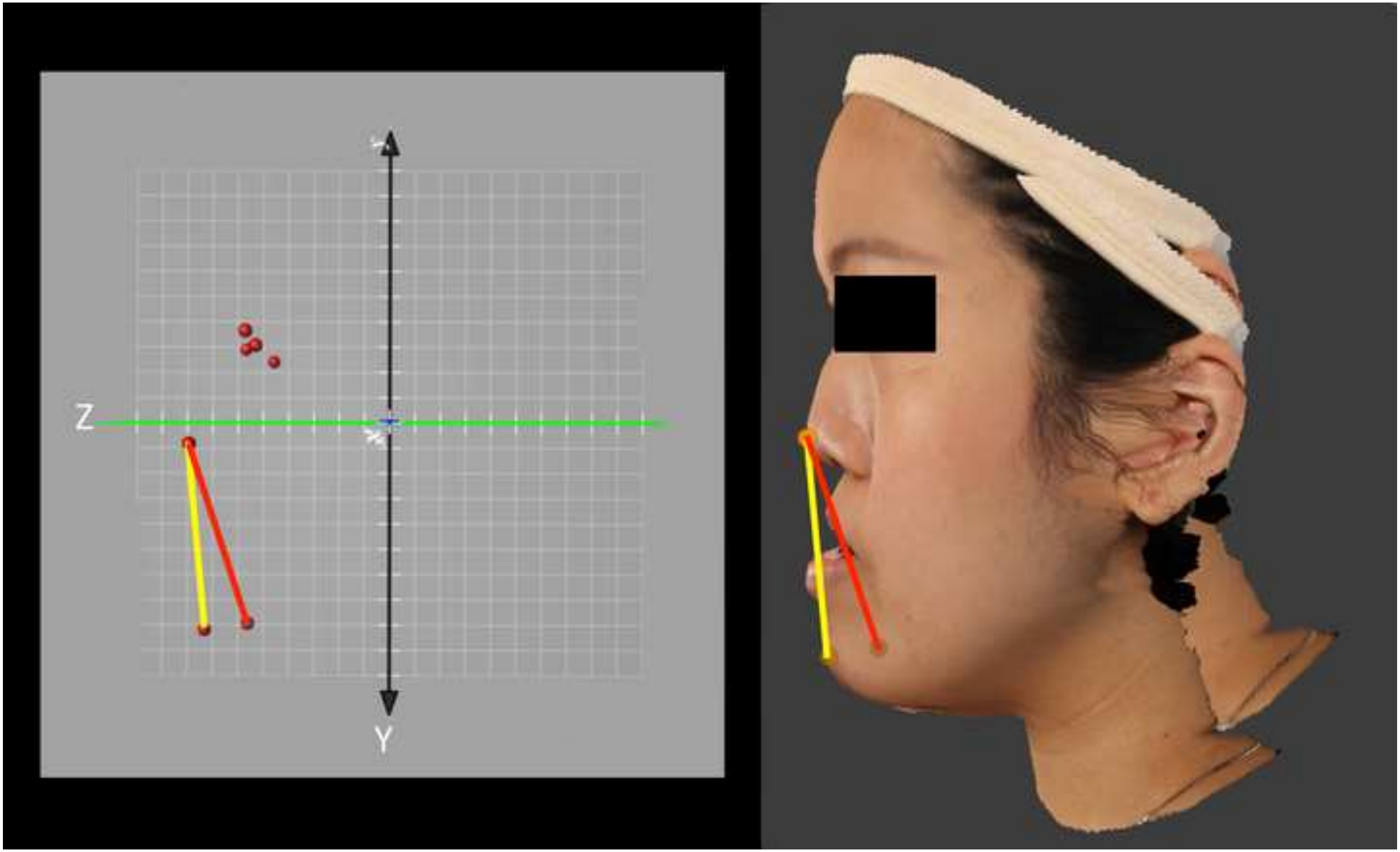

Figure 9
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