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# Quantifying faces three-dimensionally in orthodontic practice☆

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A R T I C L E I N F O

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A B S T R A C T

*Purpose:* The purpose of this study was to formulate and demonstrate a method for quantifying and visualizing the three-dimensional (3-D) configuration of the soft tissues of the face at rest to facilitate a quantitative and instantaneous understanding of a patient's static facial form characteristics.
*Materials and methods:* 3-D facial images of 200 Japanese adult volunteers at rest were recorded using a 3-D photogrammetric system. For each participant, a wire mesh fitting was conducted based on the assignment of landmarks to each 3-D facial image. This method generated 6,017 points on the wire mesh (i.e., the nodes of the fitted mesh). For each point, the mean and standard deviation were calculated and used for patient evaluation. The system performance was exemplified with three orthodontic patients with skeletal Class II and III malocclusions and laterotrusion.
*Results:* Three patients with severe skeletal Class II and III deformities and laterotrusion were evaluated with the proposed method.
*Conclusion:* A clinical method for practitioners to quantify and visualize the soft tissues of a patient's face in 3 dimensions has been presented with clinical applications and considerations. This method allows practitioners to evaluate how patients' facial characteristics differ from normative faces.


## 1. Introduction

Facial expressions play an important role as a means of nonverbal communication in the transmission of emotions and thoughts during social life; thus, facial topography influences the social acceptability and self-image of individuals. Recently, three-dimensional (3-D) stereophotogrammetry of faces has emerged in dentistry and orthopedics as a method of recording 3-D facial topography (Dindaroğlu et al., 2016). Using this technique, 3-D images are acquired by combining photographs captured from various angles with synchronous digital cameras. The advantage of this method is the lack of motion artifacts because of the short imaging time. This technology has proved to be a standard for direct measurement; the values recorded by 3-D systems are reported to be accurate and reliable for clinical use (Kuijpers et al., 2014; Metzler et al., 2014; Toma et al., 2009; Wong et al., 2008).

Conversely, several lines of evidence have shown that cephalograms are not necessary for the diagnosis and planning of orthodontic treatment because orthodontists can diagnose the condition by direct observation of the face (Atchison et al., 1991; Devereux et al., 2011; Durão et al., 2013; Nijkamp et al., 2008). A recent study showed that qualitative observation of 3-D facial and oral images for diagnosis can be an alternative (fair agreement) to the conventional method using cephalograms (Manosudprasit et al., 2017). It is expected that the use of 3-D facial images as non-radiation cephalograms for comparison with faces in the normal range would reduce the unnecessary radiation exposure caused by cephalography.

Furthermore, cephalograms can provide only profile information, whereas 3-D facial tomography provides additional information. Several recent studies (Ismail et al., 2002; Kim et al., 2010; Takigawa et al., 2017; Yamamoto et al., 2014) indicate the clinical significance of 3-D facial configurations. For example, the 3-D facial

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changes after a Wassmund osteotomy (Yamamoto et al., 2014) or bilateral sagittal split osteotomy (Kim et al., 2010) demonstrate an increase in the malar projection at rest in concert with improvements in soft tissue descent. Clinically, midfacial retrusion is one of the criteria for deciding whether to perform maxillary advancement in patients with skeletal Class III deformities. Thus, evaluating the soft tissue configurations of the face, especially the cheeks, is essential for making the correct diagnosis in combined surgical orthodontics. However, there is currently no standardized method for analyzing 3-D facial morphology that can be used in the clinical setting.

Since one of the goals of orthodontic treatment and orthognathic surgery is to reduce the deviation from the normal range of facial morphology, establishing an individualized system to visualize and measure facial forms in 3-D pre- and post-treatment would be clinically useful.

Recently, a novel method to detect 3-D mandibular changes related to soft-diet feeding in mice has been reported (Kono et al., 2017). In that study, the investigators first used a wire mesh–fitting analysis on the mandibular surface to assess the quantitative topographic variation, indicating that wire mesh fitting is a reliable and versatile method to visualize the 3-D distribution of significant differences on the surface.

Thus, the present report aimed to apply this wire fitting method on human faces to formulate a normal range of the 3-D faces in Japanese individuals. Furthermore, we will demonstrate a novel clinical method for quantifying and visualizing the 3-D configuration of the soft tissues of the face by using three patients with severe skeletal Class II and III deformities and laterotrusion at pre- and post-treatment.

## 2. Material and methods

The systems for evaluating facial morphology were divided into two parts: developing the normative faces, which included an average and standard deviation; and comparison of the patient data to the aforementioned normative faces.

### 2.1. System development

#### 2.1.1. Samples

A total of 200 participants (100 females and 100 males) aged between 18 and 35 years, were recruited from the students and faculty of Osaka University in Japan. The inclusion criteria were as follows: no congenital facial deformities including cleft lip or palate, no facial paralysis, no noticeable scars or skin disease of the neck or dentofacial regions (or history thereof), no history of any psychiatric disorder, no subjectively or objectively discernible jaw dysfunction, body mass index ranging from 18.50–24.99, dental overbite ranging from 1.0–5.0 mm, dental overjet ranging from 0.0–7.0 mm, and a straight soft tissue facial profile. A written informed consent form was distributed to and signed by all participants. The study protocol was approved by the ethics committee for medical research at Osaka University Dental Hospital (project ID: H25-E37-1).

#### 2.1.2. Data acquisition

The participants were asked to sit on a fixed chair with a natural head position without head support. They were then asked to assume a resting posture, which was defined as a relaxed facial posture with the lips in repose and the teeth in light contact in the habitual maximum intercuspation position. Each participant's face was recorded once using a 3-D digital camera (3dMDcranial System, 3dMD, Atlanta, GA, USA) with a 1.5-ms capture speed and 0.2-mm dimensional accuracy.

#### 2.1.3. Data processing

Each 3-D facial image, scaled down to 75% of its actual size, was displayed on a 17-in LCD monitor (1701FP, Dell Inc., Round Rock, TX, USA). The positions of eight single (nasion, pronasale, subnasale, labiale superious, stomion, labiale inferious, submentale, and pogonion) and five paired (Farkas, 1994) landmarks (porion, exocanthion, endocanthion, alar curvature, and cheilion; Fig. 1) were identified by visual inspection of the image and digitized using a computer mouse cursor and commercial software (Face Rugle, Medic Engineering Co., Kyoto, Japan). The process was repeated twice for each image, and the landmark coordinates produced from the two digitizations were averaged to yield the final landmark coordinates.

#### 2.1.4. Coordinate system

A coordinate system of the 3-D images recorded at rest was established based on our previous study (Tanikawa et al., 2016) (Fig. 1). In brief, the sagittal plane was defined by the exocanthion and endocanthion, and the axial plane was defined by the exocanthion, porion and subnasale. The nasion was set as the origin.

#### 2.1.5. Wire mesh fitting

For each participant, a wire mesh fitting based on the assignment of landmarks to each 3-D facial image (Kono et al., 2017) was performed using HBM software (National Institute of Advanced Industrial Science and Technology, Japan). This method generated a point cloud from the nodes of the wire mesh, i.e., a set of 6,017 data points in a 3-D coordinate system; Fig. 2 shows an example of the point cloud. The arithmetic mean and standard deviation of the

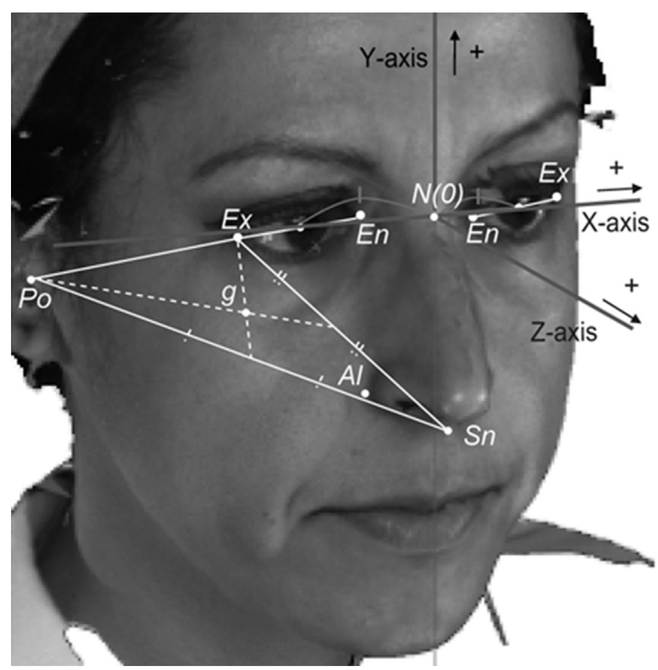


**Fig. 1.** 3-D coordinate system. The nasion (N) was defined as the origin (O). The sagittal plane was defined as a plane passing through the origin and perpendicular to the line through the midpoint of the right exocanthion (Ex) and endocanthion (En) and the midpoint of the left Ex and En. The axial plane was defined as a plane passing through the origin and parallel to the line connecting the porion and the geometric center (g) of porion (Po), subnasale (Sn) and Ex on the image projected onto the sagittal reference plane. The coronal plane was defined as a plane passing through the origin and perpendicular to both the axial and sagittal planes. Ac indicates alar curvature point; Prn, pronasale; Ls, labiale superious; Sto, stomion; Ch, cheilion; Li, labiale inferious; Sm, submentale; Pog, pogonion (cited from Tanikawa et al., 2016).

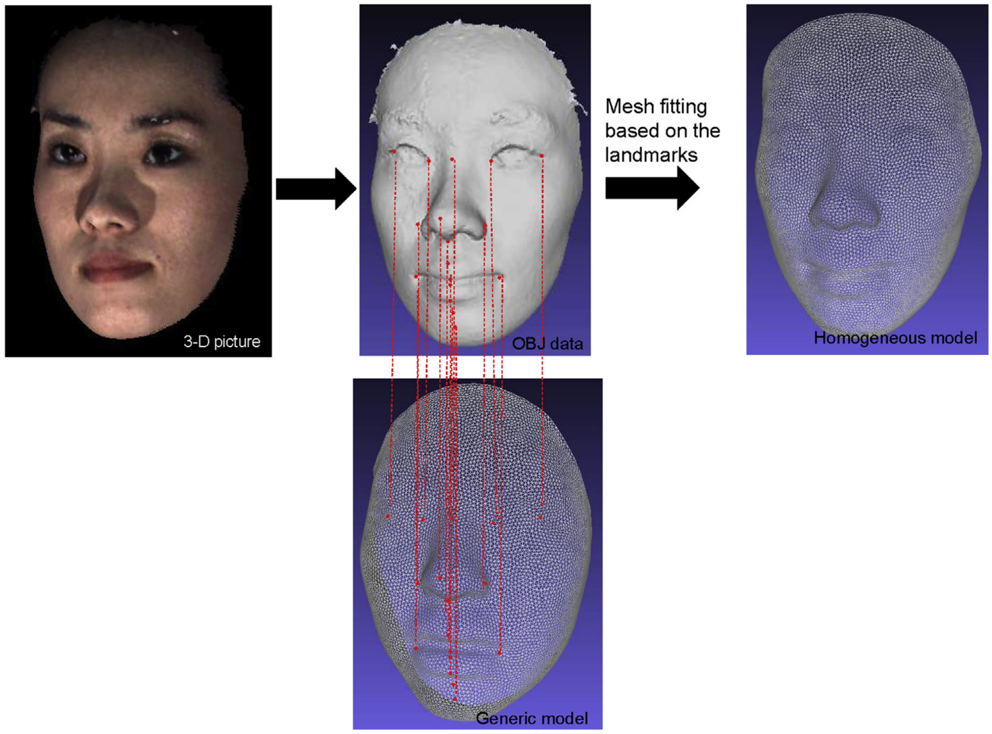


**Fig. 2.** Schematic illustration of the wire mesh fitting and the point cloud of the face that were examined.

point clouds in each ethnic group were computed, and these values were used as the normative values (Fig. 3).

### *2.2. System application: Comparison between normative faces of the sample patients*

#### *2.2.1. Samples*

To demonstrate the clinical application of the system, three Japanese patients were selected from the patients who visited our department. Case 1 was that of a 19.1-year-old female patient with Class II malocclusion, who underwent a combination treatment of anterior segmental osteotomy to reposition the anterior part of the maxilla after premolar extraction and bilateral sagittal split osteotomy (BSSO) to set the mandible forward (Yamamoto et al., 2014). Cases 2 and 3 were those of a 25.6-year-old male with Class III malocclusion and a 20.4-year-old female with laterotrusion, respectively, who underwent orthognathic bimaxillary surgery (Le Fort I maxillary surgery and BSSO). All participants signed an informed consent form prior to involvement in this study.

#### *2.2.2. Data acquisition and processing*

The 3-D images were acquired before and after treatment for each patient. The 3-D data used and the corresponding cephalogram are shown in Figs. 4–6. The patient data were processed in the same way as previously mentioned in the system development section of this paper.

The normative faces, including the mean coordinate value and the standard deviation for each sex group, were used to evaluate the patients. The equation was as follows:

$$\mathrm{Eva}_{(x,\ y,\ z)} = (\mathrm{Pt}_{(x,\ y,\ z)} - \mathrm{Ave}_{(x,\ y,\ z)})/\mathrm{SD}_{(x,\ y,\ z)}$$

where $Pt_{(x, y, z)}$ indicates the coordinate values of each image of the sample patients, $Ave_{(x, y, z)}$ indicates the average coordinate values of the control group, and $SD_{(x, y, z)}$ indicates the standard deviation of the coordinate values of the control group. To visualize the results, $Eva_{(x, y, z)}$ was visualized as a color value.

## 3. Results

### *3.1. Normative faces*

Fig. 7 shows the 3-D normative faces and the standard deviations for each male and female group. The standard deviation of the protrusion (Z-axis) of the chin was greatest, with almost 5 mm in the male group and almost 4 mm in the female group. For the vertical direction (Y-axis), the male group showed 4 mm standard deviation of the whole lower lip and chin, whereas the female group showed 4 mm standard deviation at only the top of the lower lip. For the lateral dimension (X-axis), both male and female groups showed 1–3 mm standard deviation; however, greater standard deviation of the cheek was observed in the male group when compared with the female group, along with a greater standard deviation of the facial width in the male group. (The raw data of the normative faces and the generic raw data used can be obtained via the corresponding author's e-mail address upon request.)

### *3.2. Application of the system to a Class II malocclusion case*

Fig. 8 shows the results of the application of the system to a patient (Case 1) with severe skeletal Class II deformity, before and after treatment. Figures for the Z-axis showed that the patient had a protruded upper lip (+2 SD to +4 SD) and retruded chin (−1 SD to −3 SD) before surgery. These facial characteristics were consistent with the cephalograms showing a severe skeletal Class II malocclusion due to sagittal maxillary excess and a retrognathic mandible (Fig. 4). As for the vertical dimension, the nose was positioned in a vertically higher position (−2 SD), whereas the

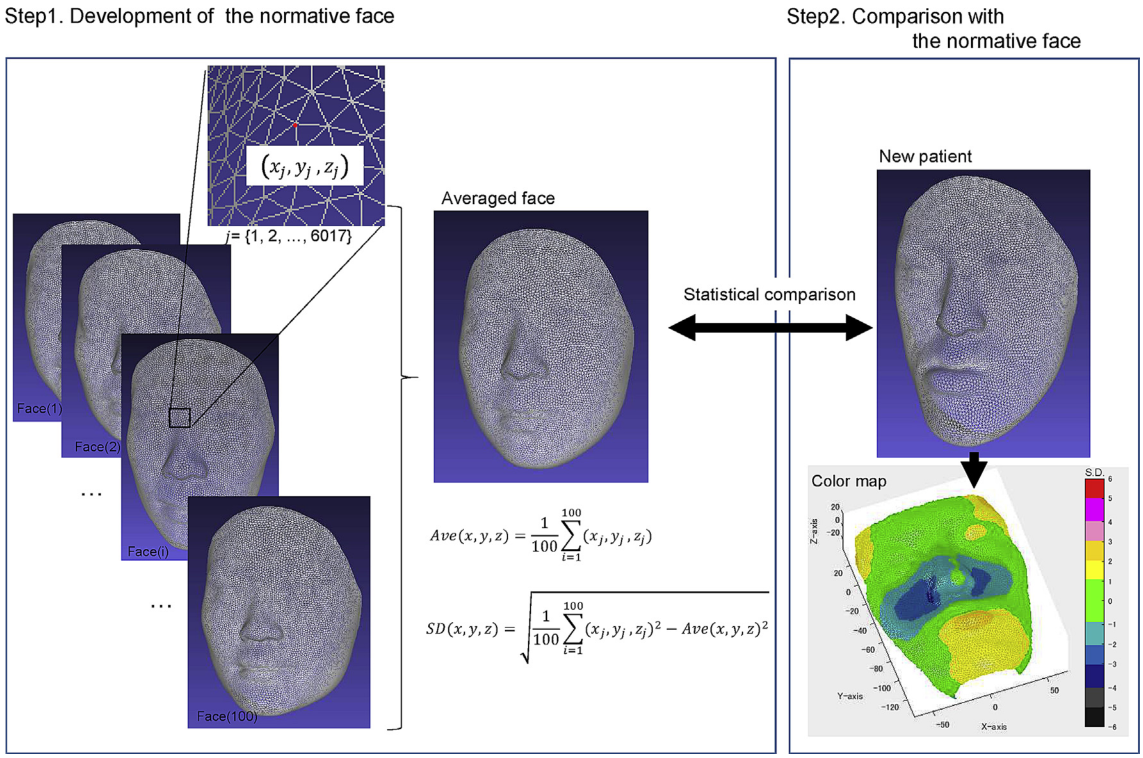


**Fig. 3.** Schematic illustration of the generation of averaged faces and their statistical analysis.

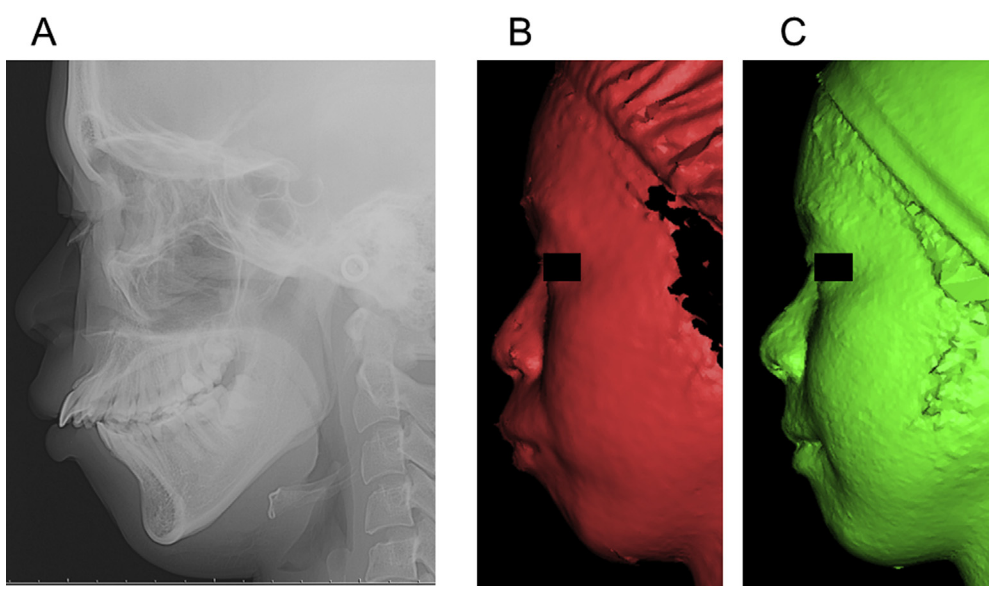


**Fig. 4.** Cephalograms of a patient with skeletal Class II deformity (Case 1) for system application (A), and 3-D image pre-treatment (B) and post-treatment (C).

anteroposterior position was within the normative range before treatment, indicating a slightly upturned nasal tip.

Postoperatively, the protrusion of the upper lip improved, yet upper lips remained +1 SD forward (Z-axis). In contrast, the chin moved forward and stayed within the normative range (−1 SD to + 1 SD, Z-axis). As for the vertical dimension, the upper lip changed from its higher position to the normative range. This means that the raised upper lip, due to the forward positioned maxilla, moved down after anterior segmental osteotomy.

Fig. 9 schematically demonstrates four types of Class II cases. Using color maps, our system can clearly discriminate between several Class II cases: maxillary protrusion combined with mandibular retrusion (A), mandibular retrusion (B), mandibular retrusion with a less protruding nose (C), and severe retrusion of the midface and the mandible (D).

These results indicate the effectiveness of the proposed method in evaluating the 3-D facial topography for Class II cases.

### *3.3. Application of the system to a Class III malocclusion case*

Fig. 10 shows the results of the application of the system to a patient (Case 2) with severe skeletal Class III deformity before and

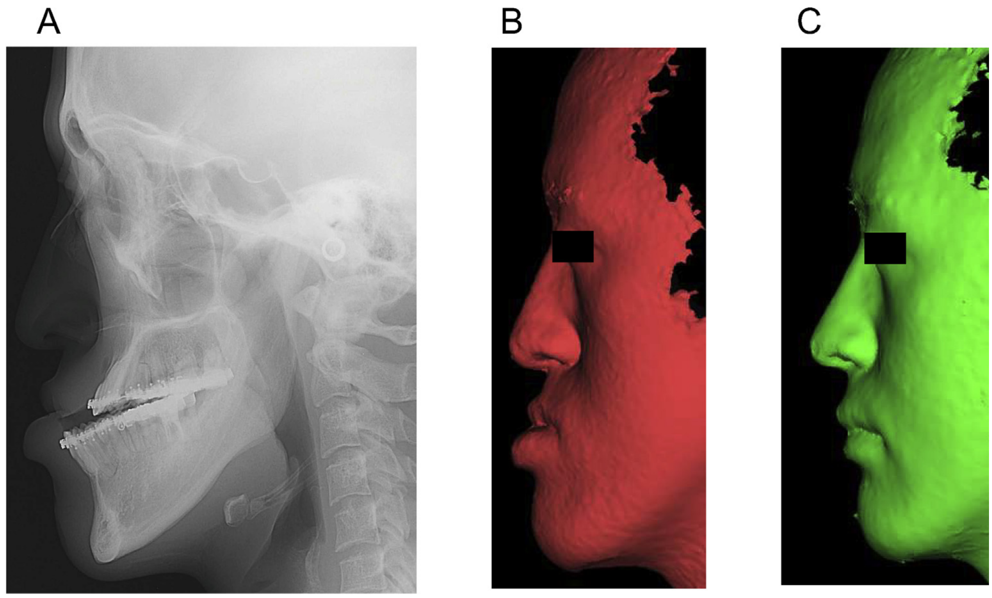


**Fig. 5.** Cephalograms of a patient with skeletal Class III deformity (Case 2) for system application (A), and 3-D image pre-treatment (B) and post-treatment (C).

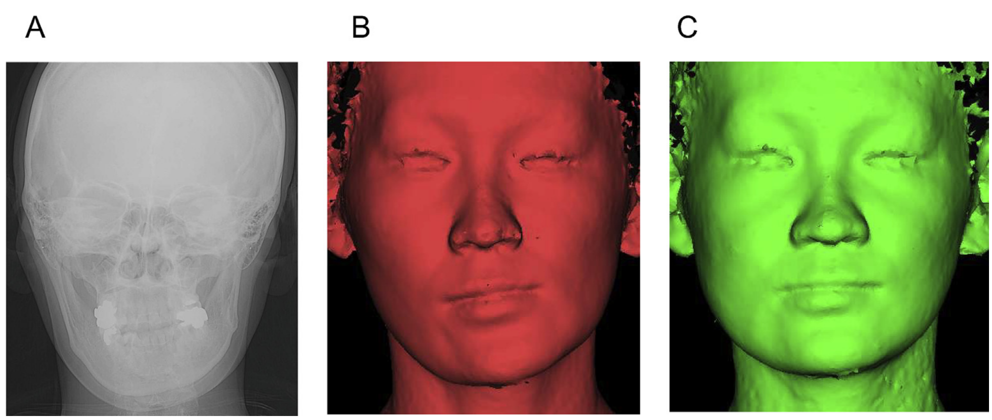


**Fig. 6.** Cephalograms of a patient with laterotrusion (Case 3) for system application (A), and 3-D image pre-treatment (B) and post-treatment (C).

after treatment. Figures for the Z-axis showed that, before surgery, the patient had a retruded midface (−1 SD to −3 SD) and protruded chin (+1 SD to +2 SD). This was easily discernible in the underlining cephalograms, which showed hypoplasia of the zygoma as well as the nasomaxillary complex (Fig. 5).

After the surgery, the retrusion at rest in the upper to middle cheek area improved remarkably, yet maintained the mean of −1 SD of the normative face on the right side (Z-axis). In contrast, the buccal region was displaced downward (Y-axis). This might be caused by the skin and underlying soft tissues not being set back in proportion to the retropositioning of the mandible. This resulted in a relatively protruded but slack upper lip area at the corner of the mouth at rest.

Fig. 11 schematically demonstrates four types of Class III cases. Using color maps, our system can clearly discriminate between several Class III cases; severe midface retrusion (A), midface retrusion combined with mandibular protrusion (B), mandibular protrusion (C), and severe mandibular protrusion (D). It should be noted that in cases A and B, retruded cheeks are easily detectable with this system.

These results indicate the effectiveness of the proposed method in evaluating the 3-D facial topography for Japanese Class III cases, including midface retrusion and/or mandibular protrusion.

### *3.4. Application of the system to a laterotrusion case*

For the patient with laterotrusion (Case 3), frontal and lateral face results before treatment (Fig. 12) show that the right nasal wing and the corner of the mouth at rest are located inferior to those on the contralateral side, with significant deviation towards the left side (Y-axis). The lip commissure is tilted when compared with the normal lip posture.

Post-treatment records exhibit remarkable improvement in the nose and lip asymmetry, which can be explained by the superior repositioning of the right angle of the mouth (X- and Y-axes). It should, however, be noted that the lip commissure still shows downward canting on the right side post-surgery, although the asymmetry of the nasal wings and the chin deviation have been corrected.

It was found that the proposed system also effectively visualized the laterotrusion case before and after treatment. Furthermore, the present case indicated that even after the skeletal abnormalities were corrected, the soft tissue problem partially remained.

Application of the system to these three cases suggests that the proposed method allows us to evaluate how patients' 3-D facial characteristics deviate from normative faces before and after treatment.

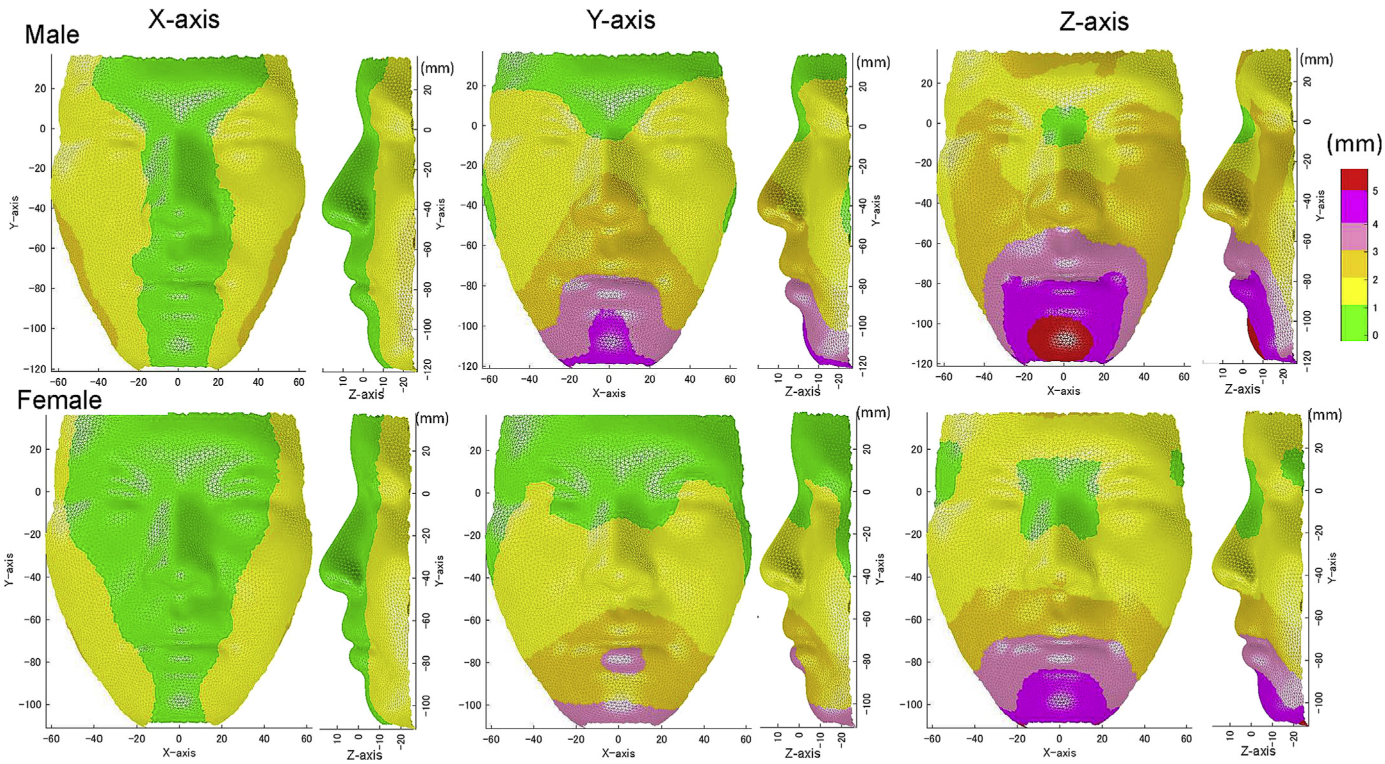


**Fig. 7.** Japanese normative range. Top: male group; bottom: female group.

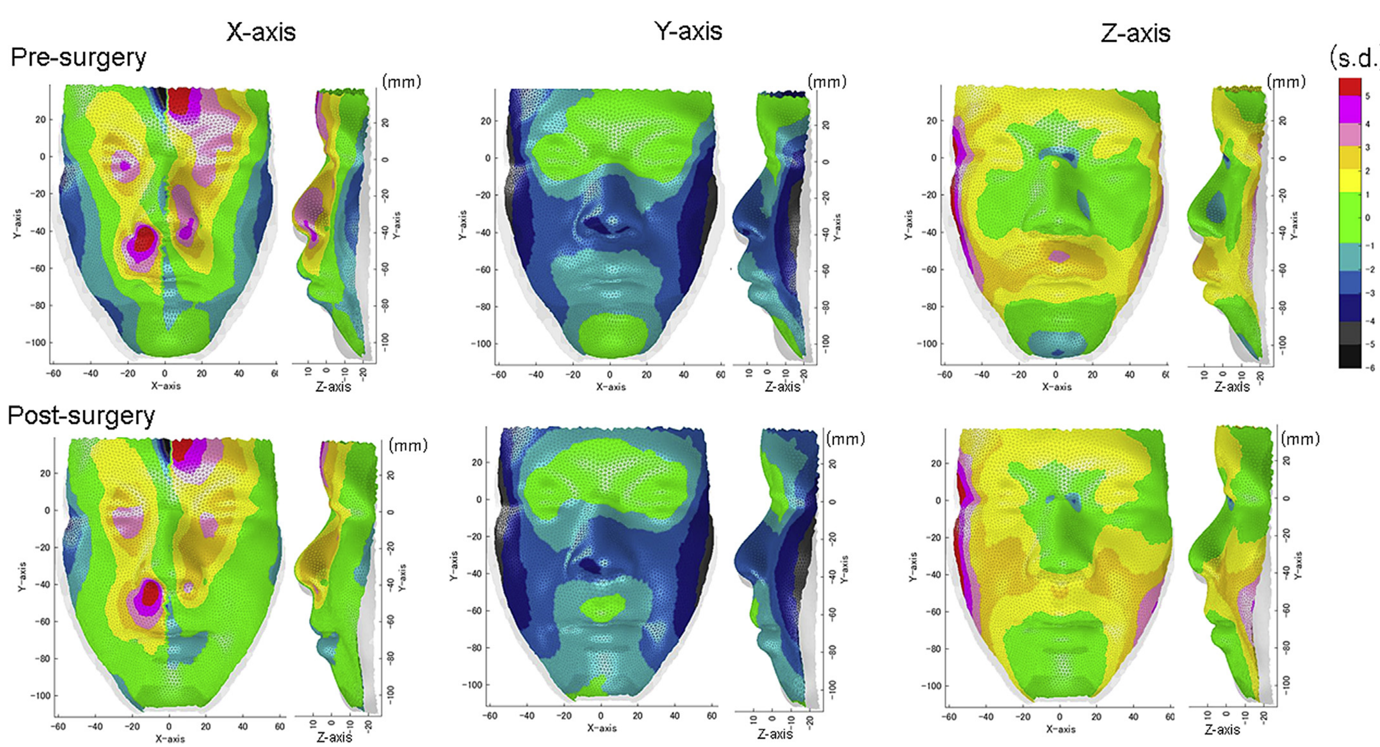


**Fig. 8.** Verification of the system using a Class II case. Gray profile indicates the averaged face. Top: pre-surgery; bottom: post-surgery. Left indicates the standardized X-values of the 3-D face when compared to the normative mean (transverse direction). Red, pink, light yellow, and deep yellow areas represent the point clouds located outwards when compared to the normative mean; light blue, deep blue, gray, and black areas/colors indicate the points located inwards (closer to the medial line); and green represents the range within 1 standard deviation (SD). In this patient (Case 1), the nasal wing was laterally widened by more than +2 SD before and after treatment. Middle indicates the standardized Y-value (vertical direction). Light blue, deep blue, gray, and black colors indicate the points located superiorly when compared to the normative mean. In this patient (Case 1), before treatment, the upper lip was located −1 SD superiorly. After treatment, the superior position of the upper lip has improved as compared to the pre-treatment position, whereas the cheek, nose, and lower lip still maintain their superior position. Right indicates standardized Z-value (anteroposterior direction). Red, pink, light yellow, and deep yellow colors indicate the corresponding point clouds located anteriorly, whereas light blue, deep blue, gray, and black indicate the points located posteriorly when compared to the normative mean. In this patient (Case 1), before treatment, the upper lip protruded by +2 SD, while the chin retruded by −2 SD. After treatment, the chin showed normal anteroposterior position, while the upper lip showed protrusion of more than +1 SD.

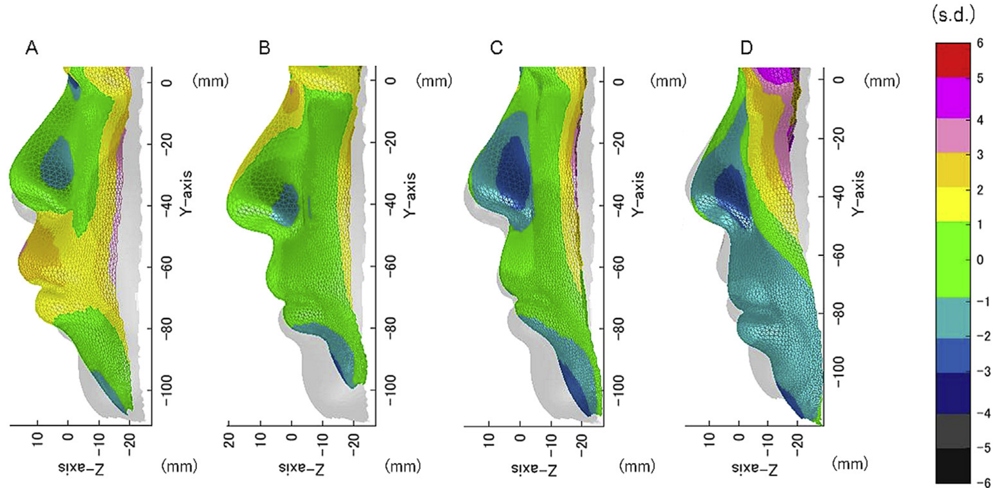


**Fig. 9.** Schematic illustration of the four types of Class II malocclusion. Only the results of the Z-axis were exemplified. Gray profile indicates the averaged face. Cephalometric values for each patient were as follows: case A, maxillary protrusion combined with mandibular retrusion (SN = 73 mm, SNA = 86°, SNB = 78°, N perpendicular to A = +8 mm); case B, mandibular retrusion (SN = 65 mm, SNA = 90°, SNB = 80°, N perpendicular to A = 0 mm); case C, mandibular retrusion with a less protruding nose (SN = 66 mm, SNA = 80°, SNB = 71°, N perpendicular to A = 0 mm); and case D, severe retrusion of the midface and the mandible (SN = 62 mm, SNA = 85°, SNB = 76°, N perpendicular to A = −5 mm). (SN: distance between the sella and nasion; SNA: angle between the sella–nasion to point A; SNB: angle between sella–nasion to point B; N perpendicular to A: nasion perpendicular to point A).

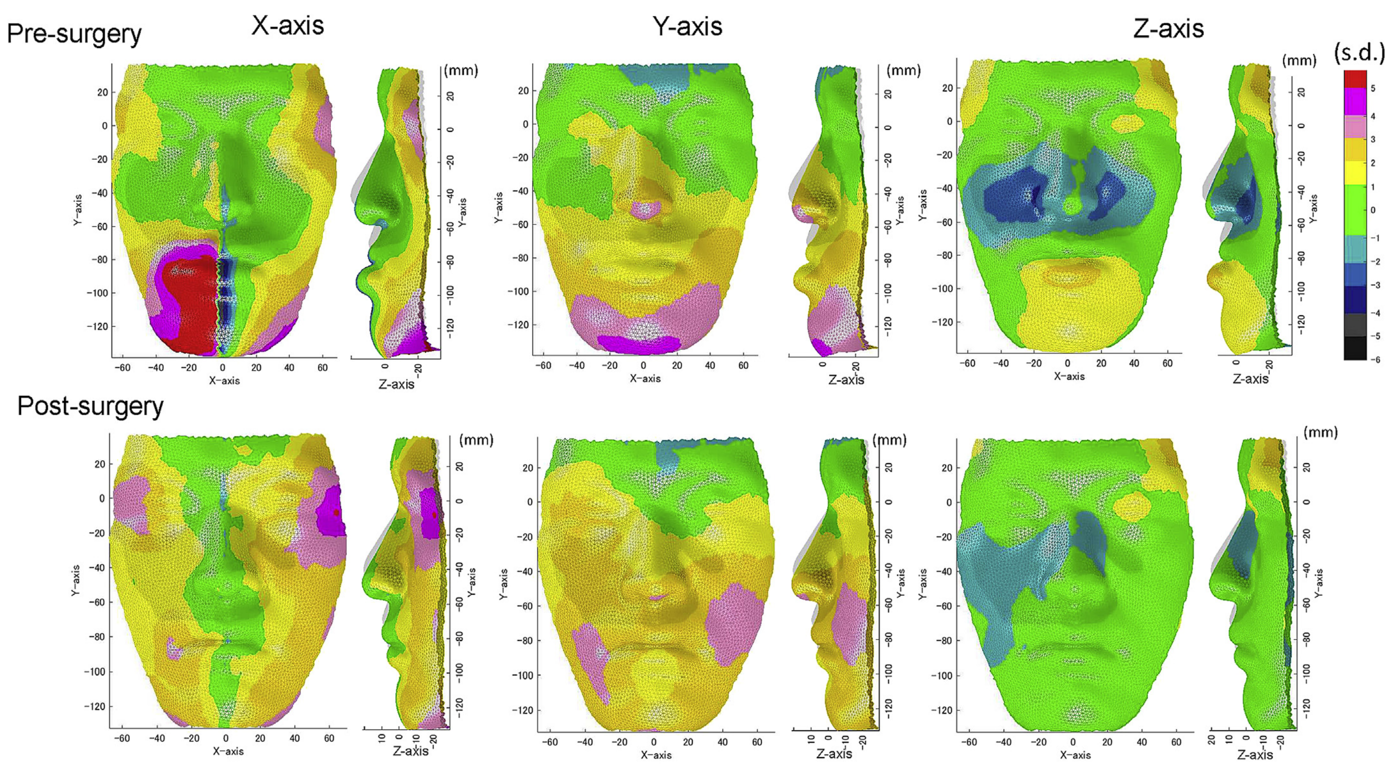


**Fig. 10.** Verification of the system using a Class III case. Gray profile indicates the averaged face. Top: pre-surgery; bottom: post-surgery. Left indicates the standardized X-values of the 3-D face when compared with the normative mean (transverse direction). Red, pink, light yellow and deep yellow represent the point clouds located outwards when compared with the normative mean; light blue, deep blue, gray and black indicate the points located inwards (close to the medial line). Green represents the range within 1 standard deviation (SD). In this patient (Case 2), before treatment, the chin was deviated to the right side by more than +6 SD. After treatment, the asymmetry improved; however, the facial width was still more than +2 SD. Middle indicates the standardized Y-value (vertical direction). Red, pink, light yellow and deep yellow indicate the corresponding point clouds located inferiorly, whereas light blue, deep blue, gray and black indicate the points located superiorly when compared with the normative mean. In this patient (Case 2), before treatment, the chin was located inferiorly by more than +5 SD and showed greater facial height. After treatment, the greater facial height improved when compared with the pre-treatment situation, while the corner of the mouth was positioned inferiorly by more than +3 SD. Right indicates standardized Z-value (antero-posterior direction). Red, pink, light yellow, and deep yellow indicate the corresponding point clouds located anteriorly, whereas light blue, deep blue, gray and black indicate the points located posteriorly when compared with the normative mean. In this patient (Case 2), before treatment, the midface was retruded by more than +2 SD while the chin was protruded by more than +2 SD. After treatment, the left halves showed normal antero-posterior position while the right halves showed slight retrusion by more than +1 SD.

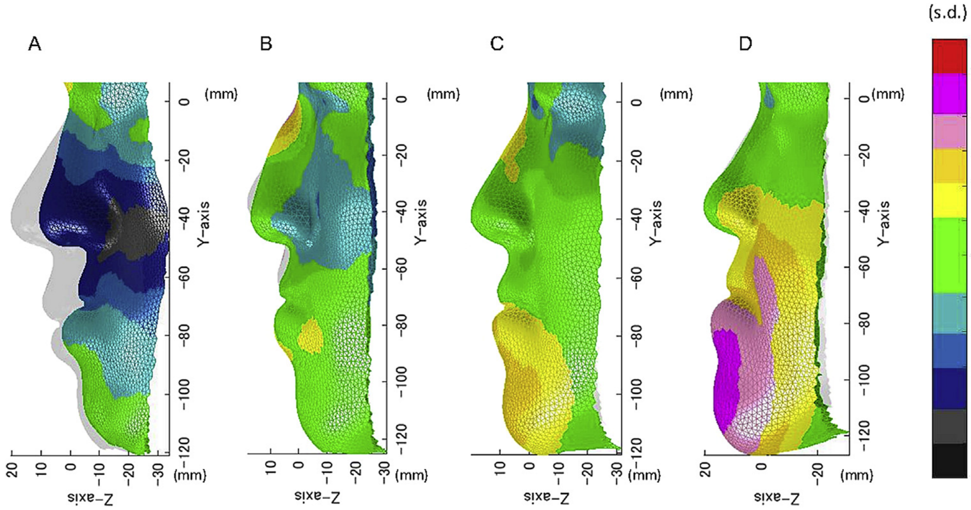


**Fig. 11.** Schematic illustration of four types of Class III malocclusion. Only the results of the Z-axis were exemplified. Gray profile indicates the averaged face. Cephalometric values for each patient were as follows: Case A, severe midface retrusion (SN = 75 mm, SNA = 81°, SNB = 83°, N perpendicular to A = −8 mm); Case B, mild midface retrusion and mild mandibular protrusion (SN = 72 mm, SNA = 83°, SNB = 84°, N perpendicular to A = −3 mm); Case C, mandibular protrusion (SN = 69 mm, SNA = 83°, SNB = 85°, N perpendicular to A = −1 mm); Case D, severe mandibular protrusion (SN = 70 mm, SNA = 82°, SNB = 87°, N perpendicular to A = 0 mm). Please note that in cases A and B, the cheeks were remarkably retruded. (SN: distance between the sella and nasion; SNA: angle between the sella–nasion to point A; SNB: angle between sella–nasion to point B; N perpendicular to A: nasion perpendicular to point A).

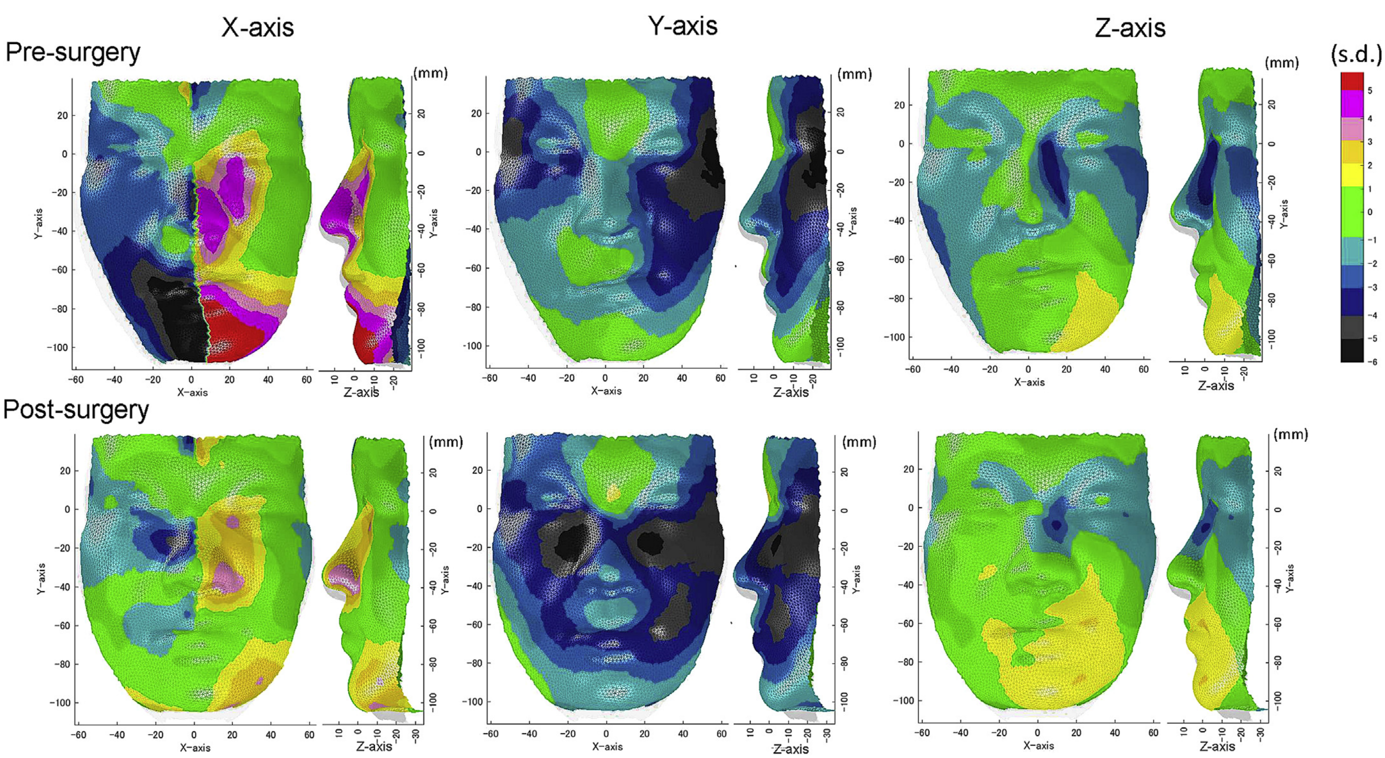


**Fig. 12.** Verification of the system using a laterotrusion case. Gray profile indicates the averaged face. Top row: pre-surgery; bottom row: post-surgery. Left column indicates the standardized X-values of the 3-D face when compared with the normative mean (transverse direction). Red, pink, light yellow and deep yellow represent the point clouds located outwards when compared with the normative mean; light blue, deep blue, gray and black indicate the points located inwards (close to the medial line). Green represents the range within 1 standard deviation (SD). In this patient (Case 3), before treatment, the nasal ala, cheek, upper lip and chin were deviated to the left side by +5 SD. The chin was deviated to the left side by more than +6 SD. After treatment, the asymmetry reduced compared with pre-treatment while the asymmetric form of the nasal ala and the left chin persisted. Middle column indicates the standardized Y-value (vertical direction). Red, pink, light yellow and deep yellow represent the corresponding point clouds located inferiorly whereas light blue, deep blue, gray and black indicate the points located superiorly when compared with the normative mean. In this patient (Case 3), before treatment, the left cheek was located inferiorly by more than +5 SD. After treatment, the cheeks of both sides were located inferiorly. The right column indicates the standardized Z-value (antero-posterior direction). Red, pink, light yellow and deep yellow represent the corresponding point clouds located anteriorly whereas light blue, deep blue, gray and black indicate the points located posteriorly when compared with the normative mean. In this patient (Case 3), before treatment, the left midface was retruded by more than +3 SD and the left chin was protruded by more than +1 SD, whereas the right halves showed less retrusion at the cheek. After treatment, the right halves showed a normal antero-posterior position while the left halves showed persistent cheek retrusion and chin protrusion.

## 4. Discussion

The method introduced in the present article helps patients, oral and maxillofacial surgeons, and orthodontic practitioners share a mutual understanding of the soft tissue abnormalities present in patients with skeletal Class II and III deformities and laterotrusion. The patient's facial soft tissues can be quantified and visualized three-dimensionally, allowing an evaluation of the deviation of facial characteristics from normative faces, which was previously not possible.

In the present study, the averaged faces of the Japanese population as well as the standard deviation of the whole face were presented. As a result, the standard deviation of the X-, Y- and Z-coordinate values differed between males and females in a site-specific manner. The male group showed a greater area ranging from the subnasal area to the chin, with a deviation greater than 3 mm in the Z-axis. In particular, Japanese males had a greater standard deviation of the chin (greater than 5 mm). This result corresponds to the greater prevalence of skeletal Class III deformities in Japanese people (Ishii et al., 2002). In other words, the chin protrusion in the Japanese male group should be acceptable when compared with the normative range of the population used in the present study. The standard deviation in the X-axis was smaller than in the Z-axis in both sexes. This result indicates that the transverse deviation is easily detectable when compared with chin protrusion.

In dentistry, 3-D quantitative analysis of the craniofacial structures is crucial to determine the treatment objectives and/or to assess treatment effectiveness. The vast information included in 3-D structures has often been simplified as angles and distances, or, at best, as surface area measurements or volumes in conventional anthropometric analyses, while additional information such as surface topography has been ignored. Furthermore, the normal range has not been considered in previous studies. Studies that analyzed the surfaces have only depicted differences before and after treatment (Atchison et al., 1991; Manosudprasit et al., 2017). To the best of our knowledge, there is no method to statistically compare surface coordinates between a patient and the control group having normal occlusion. This is the first report to introduce a system that compares the patient coordinate values with the normal range incorporating the standard deviation.

The reason why 3-D analysis has not made further progress can be attributed to the technical challenges in analysis of 3-D structures, e.g., computation cost, algorithm complexity and visualization difficulties. To solve the problem of all 3-D images containing an enormous quantity of information that is not fully utilized, this study developed a new method to statistically analyze entire 3-D morphologies and to visualize the results in a simplified way.

In short, conventional two-dimensional photographs blur the true topographic characteristics of the patient's face in three dimensions; however, the combined use of a system that can portray the patient's facial surface configuration by superimposing a mean configuration can enable effective documentation of the site and severity of a deformed portion of the face.

There are several limitations in the present study. First, when analyzing faces anthropometrically, it is well known that ratios are important to express facial attractiveness (Farkas, 1994; Ishii et al., 2002). The present system does not detect ratios. Further calculation of ratios should be added to this system. The normal ranges of the ratios, distances and angles of anthropometric measurements have been described in other studies (Tanikawa et al., 2016). Second, the sample size for exemplification of the system application was small in the present study. Thus, it is still unclear whether the use of the proposed system with 3-D facial images is superior or equivalent to the use of conventional cephalograms. Further research should aim to compare the proposed system and the conventional system when diagnosing the patient, to enable wider use in the clinical setting.

## 5. Conclusions

A convenient clinical method to quantify and visualize patients' facial soft tissues in three dimensions has been presented, with clinical applications and considerations for oral and maxillofacial surgeons and orthodontic practitioners. The method allows us to evaluate how patients' 3-D facial characteristics deviate from normative faces.

## Acknowledgements

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcms.2019.02.012.

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