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博 士 論 文

3D Quantification of the condylar and glenoid fossa remodeling following orthognathic surgery on class II and class III skeletal malocclusions

（II 級・III 級骨格性不正咬合に対する顎矯正手術後の下顎頭および下顎窩リモデリングの３次元的解析）

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Contents

Abstract

Among many factors that contribute to the stability of the orthognathic surgery, the changes in the condyle, glenoid fossa and condylar position may play a role. So far, no study has ever considered the relationship between the change of temporomandibular joint (TMJ) structures with the newly adopted position of condyle within glenoid space. In the past, the changes in condyle were evaluated by 2D cephalograms method which has many drawbacks due to the overlapping of anatomical structures. The introduction of Computed tomography (CT) with 3D reconstruction has revolutionized the way dentofacial skeleton is analysed since it allows precisely locating changes that happened in a specific area.

This study aimed at investigating the remodeling pattern occurring within the bony structures of TMJ after surgically corrected class II and class III malocclusion patients using 3D technique, discovering the relationship between the remodeling of the condyle, the glenoid fossa, and the change of the condylar rest position, and finally identifying the patient's clinical characteristics that may involve in the remodeling process.

A retrospective study was conducted based on the pre-operative and 1-year postoperative CT scans of patients who received orthognathic surgery at Hokkaido University Hospital between 2011 and 2021. Patients were separated into class II (21 patients) and class III

(20 patients) skeletal malocclusions. 3D segmentation of condyles and cranial bases was automatically constructed using ITK-SNAP software. Voxel-wise superimposition relative to the cranial base of the pre-operative and post-operative CT images were obtained utilizing 3D slicer software and the 3D surface models were created. Condylar remodeling was assessed by total volume change and surface distance between corresponding points in the regions of interest (ROI). Glenoid fossa remodeling was measured by the surface distance between the closest points in the ROI. The association between the remodeling of TMJ bony structures and the condylar position was tested by Spearman's correlation. The influence of clinical characteristics and surgical interventions on remodeling was analysed using Spearman's correlation and binary logistic regression model.

Our result showed that the condylar volumes were significant decreased in class II patients and increased in class III patients after surgery ($p<0.01$). The condyle and glenoid fossa experienced remodeling of less than 1.5mm and 1mm respectively. In regions of interest of condyle, in both class II and class III patients, the anterior-lateral, superior and posterior were the regions that showed the largest change. There was no difference amongst the regions of interest of glenoid fossa regarding the remodeling amount. Condylar position changed around 2mm after surgery in both class II and class III patients.

Positional change of condyle at the jaw rest position had a weak correlation with condylar remodeling ($p<0.05$, $0.2\leq |r|\leq 0.4$), but no association with the glenoid fossa remodeling ($p>0.05$). Mandibular surgery, Wits appraisal, overjet, and ANB were correlated with mandibular head volume change, and these factors were considered risk factors for mandibular head volume reduction in a binary logistic regression model ($p<0.05$). In the glenoid fossa, it was suggested that the overbite may affect the anterior and medial surfaces, and the ANB may affect the upper surface remodeling($p<0.05$).

In summary, our study found that the volume of condyle tended to decrease after surgery in class II patients and increase in class III patients. Although both the condyle and glenoid fossa experienced some changes after orthognathic surgery, those changes did not show a relevant influence on the change of condylar rest position. However, considering the importance of condylar position after surgery to surgical stability, future study on the factors that affect the condylar position is necessitated.

1. Introduction

Many researchers have pointed out that condyle and glenoid fossa can experience some morphological changes in accordance with the change in the surrounding environment regardless of growth potential.[1-7] However, to date, most studies on adaptive condylar and glenoid fossa remodeling focused on the change over time under the orthodontic force produced by functional appliances.[3-7] In the case of orthognathic surgery, the surgery causes an acute change in the nature of the dentofacial pattern. We, therefore, hypothesized that the condyle and glenoid fossa would remodel in synchrony with the newly established environment. In the orthognathic surgery, the goal is to obtain a stable occlusion in the long term postoperatively. The occlusal relapse is the most common problem. Various factors have been described to link with post-surgical instability such as improper planning, maxillary down-grafting, large mandible advancement, and progressive condylar resorption.[8, 9] Among them, the displacement of the condylar head was thought to be one of the causative factors for early relapse.[10, 11] However, Ueki et al in their review of the temporomandibular joint (TMJ) morphology in different skeletal patterns hypothesized that the position of condyle after surgery was not necessarily the same as the pre-surgical position, but the newly established masticatory and skeletal system imposed force with different magnitude and directions on the condyle would change its location eventually.[12] So far, no research has ever considered the relationship between the change of TMJ structures with the newly adopted position of condyle within glenoid space.

In the past, the change of condylar morphology was evaluated by 2D cephalograms. This method clearly has many drawbacks due to the overlapping of anatomical structures. The introduction of computed tomography (CT) with 3D reconstruction has revolutionized the way dentofacial skeleton is analysed ever since it was introduced. Also, CT has been validated as the reliable method for three-dimensionally measuring the maxillofacial change with small variabilities. Among the 3D analysing techniques, SPHARM (Spherical Harmonic Description) has been applied quite extensively in analysing condylar change due to osteoarthritis, since it allows locating and measuring changes in a specific area precisely.[13] The disadvantage of SPHARM analysis is it only can be applied to objects with spherical topology. –

If the morphology of the bony structures of TMJ can be examined in detail, we believe that will be useful in the analysis of clinical and surgical factors affecting the post-operative relapse. Therefore, this study’s objectives were to quantitatively measure the remodeling of TMJ bony structures including condyle and glenoid fossa in patients with class II and class III dentoskeletal malocclusions after orthognathic surgery using 3D techniques, discover the relationship between the remodeling of the condyle, the glenoid fossa, and the change of the condylar rest position, and finally identify the patient's clinical characteristics that may involve in the remodeling process.

2. Materials and Methods

Considering the retrospective nature of this study, the written consent forms were waivered by the Medical Ethics Committee of Hokkaido University No.016-0170. This research was processed under the statement of the Declaration of Helsinki.

2.1 Study design

This is a retrospective study conducted based on 3D models constructed from the pre-surgery and post-surgery CT images of patients who received orthognathic surgery at the Hokkaido University Hospital between 2011 and 2021. The following selection criteria were applied: No condylar degenerative diseases such as osteoarthritis or osteoarthrosis at the time of treatment as well as the follow-up, bimaxillary surgery with Le Fort I for maxilla and sagittal split ramus osteotomy (SSRO) for the mandible, no facial asymmetry (The bony Me point coincides or deviates of less than 4 mm from facial midline), not under temporomandibular joint disorder (TMD) treatment, no history of trauma, no dentofacial deformities related to congenital syndrome or systemic diseases such as cleft lip and palate, or hemifacial microsomia, CT data before and 1-year follow-up were available, patient clinical characteristics were adequately recorded.

Patients were divided into a class II patient group with ANB $\geq$ 4 degrees and a class III patient group with ANB $\leq$ 2 degrees at the time of examination.

2.2 Study variables

The main predictive variable was the type of dentoskeletal malocclusion, which was divided into class II and class III groups. The main outcome variables were the amount of condylar and glenoid fossa remodeling 1-year post-operatively in mm. The secondary outcome variables were the amount of the condylar rest position change and its correlation with the remodeling of bony structures. Other variables were patient demographic information (age, gender), clinical characteristics (Wits appraisal, overjet, overbite, SNA angle, SNB angle, ANB angle, Sn-Mp angle, Occlusal plane angle change), and range of surgical intervention in mm.

2.3 Surgery

Patients with class II and class III malocclusions all received orthodontic treatment around 1.5-2 years on average before orthognathic surgery. Surgeries were performed by skilled doctors at the same team of orthognathic surgery at the Department of Oral and Maxillofacial Surgery, Hokkaido University Hospital. The Le Fort I surgery on the upper jaw was carried out first, followed by SSRO on the lower jaw. For fixation, four L-shaped titanium miniplates were placed on the upper jaw at the nasomaxillary buttress and zygomaticomaxillary buttress. In the operated mandible, 2 titanium miniplates were placed on each osteotomy side. One straight plate was placed across the vertical osteotomy line on the buccal surface of the mandible and one L-shaped plate was positioned over the oblique osteotomy line behind the last molar. Patients were hospitalized for 1 week after surgery to monitor post-operative complications. Then intermaxillary elastic traction was delivered to guide the occlusion. The orthodontic treatment was resumed 1 month after surgery and continued up to 1-2 years after surgery in most cases.

2.4 Data collection

Pre-operative and post-operative (T0 and T1 respectively) CT scans of the head and neck region were taken right before the surgery and 1 year after surgery. The patients were instructed to lie supine inside the gantry with their Frankfort horizontal plane oriented perpendicular to the floor. Patients were asked to relax their lower jaw, and then gradually close it until the first occlusal contact was sensed. Also, the patients should hold this jaw position still and thus avoid swallowing during taking CT. This position is mandibular rest position in supine posture attained by verbal instruction, and condyle at this position was called the condylar rest position in this study.

All CT images were taken by the same CT machine, CANON Aquilion PRIME: 135V; varying tube's current, varying exposure time, the field of view = 250mm). All the images were saved as the digital imaging and communication in medicine (DICOM) file, then exported to the 3D Slicer software (https://www.slicer.org/) to resample into isotropic voxel size of 0.4x0.4x0.4mm.

The condylar remodeling was assessed by both global volume change and bone resorption/apposition in regions of interest. The protocol was employed to analyse images for the change of condyle as described by Cevidanes[15] and Zupnik[16] with our modifications to facilitate the measuring process. In brief, the segmentation of the cranial base was constructed using ITK SNAP software (http://www.itksnap.org/pmwiki/pmwiki.php). The cranial base segmentations were imported to the 3D slicer for superimposition of T1 to T0 images relative to the cranial base using Voxel registration method (Voxelbase registration, 3D slicer). The registered T1 and T0 CT images were imported back to ITK-SNAP for segmentation of the mandible. The lower threshold was set at around 300-350 HU, and the upper threshold was set at around 2000 HU. To facilitate the measurement of condylar remodeling, glenoid fossa remodeling and condylar displacement, another segmentation with pre-marked anatomical landmarks on the condyle and glenoid fossa (highest point, center of lateral surface, center of medial surface, center of anterior-lateral surface, center of anterior-medial surface, center of posterior-lateral surface, center of posterior-medial surface) was made (Supplementary figure 1-1,2-1). The segmentations of both the cranial base and mandible were converted to the surface models, and reoriented to coincide with the common coordinate system of the 3D Slicer (Model maker, transform module, 3D slicer) (Figure 1). The T0 and T1 surface models were then converted into triangle surface meshes containing 4002 corresponding points. The corresponding models were computed in three steps using the Shape analysis module of 3D Slicer. First of all, the surface model of both T0 and T1 were inputted into the Shape analysis module. Using a subdivision value of 20 and a degree of 25 for Spherical harmonic function, the surface model was converted into surface meshes containing 4002 points. In the next step, the surface meshes were resampled into a unit sphere using area-preserving and distortion-minimizing spherical mapping processes. The individual point on the sphere has its own 3D coordinate system. In the last step, the first-order ellipsoid from spherical harmonic coefficients was employed to align and establish correspondence across the T0 and T1 surfaces. Parameterized T0 and T1 spheres were then converted back to surface models. Those models were SPHARM-PDM models (Figure 2).

To calculate condyle volume, the T0 SPHARM-PDM model was used as the template to register the T1 SPHARM-PDM model by the Procrustes alignment method. The condylar head was separated from the rest of the mandible by two planes going through the lowest point of the sigmoid notch, the horizontal plane was parallel to the Frankfort plane and the vertical plane was perpendicular to the horizontal plane (Easy Clip, 3D Slicer). Since the T1 model had been registered to the T0 model by the Procrustes alignment method, the same cutting planes could be applied at the same time. The volume of the condyle was recorded (Figure 2) (Information tab of Model module, 3D Slicer).

The remodeling of condyle was evaluated in 7 regions of interest (ROI) (Figure 3), and each ROI had a diameter of 7mm (Pick and Paint, 3D slicer). Because T0 and T1 models had been converted to the models with the corresponding points on the surface, the remodeling amount was calculated using the signed point-to-point distance method (Mesh statistic, 3D slicer). In this step, the color-mapped model which contained all the information about the distance between the corresponding point of the T0 and T1 models was generated. The negative value indicated bone resorption, the positive value signified new bone formation. Given that the SPHARM-PDM algorithm does not allow computing pre-marked models and the difficulty of accurately defining landmarks on the 3D models, the model with pre-marked anatomical landmarks and the colour-mapped model were merged as shown in Supplementary figure 1-2 to help identify the centre of ROI.

The calculation of the glenoid fossa remodeling was carried out on the surface model. After superimposing T1 images to T0 images relative to the cranial base as described above, the surface models were generated. The glenoid fossae were separated from the rest of the cranium using the following planes: the planes going through the lowest point of the articular eminence anteriorly and inferiorly, the anterior surface of the exterior auditory meatus posteriorly and the cross-section of the inferior plane and medial surface of the glenoid fossa. The remodeling of the glenoid fossa was evaluated in 7 regions of interest (ROI), and each ROI had a diameter of 7 mm (Figure 4). The remodeling amount was measured using the distance between the closest point on surface models (Pick and Paint, Mesh statistic, 3D slicer). After generating a color-mapped model as described above, the pre-marked anatomical landmarks and the color-mapped model were merged as shown in Supplementary figure 2-2 to help identify the centre of ROI.

The amount of condylar displacement between T0 and T1 when mandible at rest was measured using landmark prelabelled models registered to the cranial base. Only the distance between the highest points of the condylar heads of the T0 and T1 models was used to record the displacement of the condyle, and then propagated to three axes X, Y, and Z of rectangular coordinates (Figure 5).

2.5 Data analysis

The data were analyzed with IBM SPSS software (version 26.0, IBM Corp, Armonk, USA). The level of significance was set at 5%. The Shapiro-Wilk test was used to test whether the samples were normally distributed. The paired-samples T-test was used to compare the condyle volumes at T0 and T1. Independent samples T-test was used to compare the demographics and clinical characteristics of patient pre-surgery and post-surgery. One-way ANOVA test, Welch's ANOVA with post-hoc analysis using the Bonferroni test were used to evaluate condylar and glenoid remodeling in regions of interest within the group. Mann-Whitney U test was applied to compare the difference in condylar and glenoid remodeling between the class II and class III groups. Spearman's correlation was used to determine the relationship between the condylar remodeling, glenoid fossa remodeling and the change of condylar rest position. Also, Spearman's correlation and binary logistic regression model were used to evaluate the factors that might involve in the remodeling process.

3. Results

Table 1 summarized the demographics and clinical characteristics of the patients. Twenty-one class II patients (17 women, 4 men, mean age=29.35±9.58) and twenty class III patients (13 women, 7 men, mean age=28.08±11.20) were recruited for this study. All class II patients had Wits value >0mm. All class III patients had Wits <0mm. Class II patients had the overjet value, Sn-Mp angle, and the range of maxillary and mandibular surgery were significantly different from class III patients ($p<0.01$, independent samples T-test).

3.1 Condylar remodeling

The mean condylar volume significantly decreased after surgery in class II patients and increased in class III patients post-operatively ($p<0.01$, paired samples T-test) (Table 2). In addition, class II patients tended to experience condylar volume reduction 8.46 times higher than class III patients (p=0.00, OR=8.46, CI=3.13-22.81, Chi-squared test).

In different regions of interest of condyle, all the changes, either resorption or apposition, are less than 1.5mm on all surfaces of interest (Figure 6). Intraclass comparison using the Welch-ANOVA test showed that the remodeling amount was different between the locations (p=0.00 in class II, p=0.01 in class III). Specifically, post-hoc analysis using Bonferroni's test showed that superior, posterior and anterior-lateral surfaces were the areas that experienced the most change, the surface showed the least change was the lateral surface (class II) and the medial surface (Class III) (Figure 6). Comparing the absolute amount of condylar change between the two groups showed that class II and III only differed in lateral and posterior-medial surfaces (p=0.01, Z-score=-2.52 and p=0.00, Z-score=-2.31 respectively). Specifically, Class II patients showed more change in posterior-medial surface than class III patients. In contrast, the lateral surface in class III patients was subjected to more remodeling than in class II patients (Table 3).

3.2 Glenoid fossa remodeling

The remodeling of the glenoid fossa in different regions was generally less than 1mm, with few exceptions (Figure 7). Welch's ANOVA test showed that the absolute remodeling of different regions in the glenoid fossa was not different ($p=0.06$ in class II, $p=0.83$ in class III). Interclass comparison using the Mann-Whitney U test showed that there was no statistical difference between Class II and Class III across the glenoid surfaces (Table 4).

3.3 Influence of condylar and glenoid remodeling on the condylar rest position

There were no significant differences among the three axes in terms of displacement amount of condyle ($p=0.33$ in class II, ANOVA; $p=0.87$ in class III, Welch-ANOVA), and all values in three axes were less than 2mm (Figure 8). Spearman's correlation model showed that condylar remodeling in the posterior-medial surfaces had a weak relationship with shifting rest position medial-laterally ($p=0.02$, $r=-0.26$). Remodeling on the anterior-medial, anterior-lateral, and superior condylar surface showed a weak relationship with the anterior displacement of the condylar rest position ($r=0.25$, $r=0.26$, and $r=-0.25$, respectively) (Table 5) There was no correlation between the glenoid fossa remodeling and shifted condylar rest position in 3 different axes ($p>0.05$)

3.4 Factors related to the remodeling of the condyle and glenoid fossa

In the condyle, Spearman's correlation and binary logistic regression model suggested that occlusal change, overbite, and range of maxillary surgery did not have a relationship with the total volume change of condyle ($p>0.05$). Increasing ANB, Wits, overjet and, surgery advancement of the mandible, which were all related to class II skeletal tendency tended to have more condyle volume reduction ($p<0.05$, $r=-0.47$, $r=-0.37$, $r=-0.38$, $r=-0.27$, respectively). Specifically, if other independent variables were constant, for every 1mm-increase in mandibular advancement, Wits value, overjet, and 1-degree increase of ANB angle we expected 1.17, 1.09, 1.19 and 1.19 increase the in the odds ratio of condylar volume reduction, respectively (Table 6). Concerning the remodeling in regions of interest in the condyle, maxillary surgery showed a weak correlation with remodeling on the anterior-lateral surface and overbite showed a weak correlation with the remodeling on the posterior-lateral surface ($r=0.33$ and $r=0.26$, respectively). Mandibular surgery, ANB, overjet a showed a weak to moderate correlation with the remodeling on medial and anterior surfaces, while ANB also showed a weak relationship with remodeling on the lateral surface ($r=-0.2$) (Table 7) In the glenoid fossa, overbite showed a weak relationship with the remodeling on the anterior surface ($r=0.26$ for anterior-medial surface, $r=0.22$ for anterior-lateral surface) and medial surface ($r=0.23$), ANB showed a weak correlation with the remodeling on the superior surface ($r=-0.24$) (Table 8).

4. Discussion

To the best of our knowledge, this is the first study in the field of orthognathic surgery investigating the remodeling pattern of bony structures of TMJ including both condyle and glenoid fossa. This is also the first to discover the relationship between TMJ bony structures change and the shifting of the condylar rest position.

In our study, while condylar volume in class II patients significantly decreased after surgery, the opposite tendency was observed in class III patients. Condylar volume reduction after mandibular advancement surgery in class II patients has been reported in many studies. [17-19] The number of studies concerning the behaviour of condyle after surgery in class III patients is rare in comparison to class II, and most of them confirmed that after surgical correction, the condyle experienced some morphological changes.[20, 21] Podčernina et al in their research on condylar status in bimaxillary as well as maxillary advancement alone in class III patients, however, did not observe a significant increase in condylar volume one-year follow-up. [22] The difference may be generated from the difference in the volume measuring method. In our study, before separating the condylar head from the rest of the mandible by a plane parallel to Frankfort horizontal plane, the T1 model was registered to the T0 model to make sure that they both have the same orientation in 3-dimensional space.

We also addressed the difference in remodeling in different regions of the condylar head. In both class II and class III patients, the remodeling prominently happened on the superior, posterior and anterior-lateral surfaces. As for the attachment of the muscle to the condyle, it is well known that the inferior belly of the lateral pterygoid muscle attaches to the anterior-medial surface of the condylar head. On the other hand, concerning the anterior-lateral side, which muscle gets involved is not clearly known. Akita et al described the presence of the muscle attached to the anterior-lateral surface of the condyle and named it the midmedial muscle bundle of the temporalis. It was not an exceptional bundle and was found in almost all individuals.[23, 24] Therefore, we were of the opinion that these muscles might contribute differently to the remodeling of the condyle on the anterior-medial surface and anterior-lateral surface. Our result is reciprocated with the findings from the 2D model on class III patients of Park et al [25] and the 3D model on class II of Claud JDP et al.[17] Although the research of Jung et al [19] agrees with our research that the posterior segment was subjected to the highest change, the anterior segment was the least to change. This difference may be explained by the difference in the region definition. Jung divided the anterior region and posterior region by the plane going through the medial and lateral poles of the condyle perpendicular to the axial plane. In our research, we separated the anterior region into the anterior-lateral region and anterior-medial region, taking the difference in muscle attachment in mind.

The glenoid fossa is a rare subject of investigation in orthognathic surgery. Previous studies mostly paid attention to its volumetric change.[17, 18, 26] The dimension of glenoid space, however, is affected by the location of the condylar head. Studies on structural change of the glenoid fossa in animal experiments after continuous advancement of the mandible caused changes mostly in the anterior and posterior surfaces of the glenoid fossa.[6, 7] Our results, however, did not find any pattern of remodeling in both groups of patients. This difference can be explained by the difference in the nature of treatment modalities employed. In the mandibular advancement experiment, the advancement force was delivered and directed in a specific direction, which resulted in specific patterns of change in the glenoid fossa. In orthognathic surgery, however, the patient experienced a sudden change in skeletal pattern and soft tissue profile. The adaptative change in the glenoid fossa in response to the new surrounding environment, therefore, did not follow any specific pattern.

While investigating the response of bony structures of TMJ following orthognathic surgery, we hypothesized that the remodeling of the condyle and glenoid fossa would affect the overall volume of glenoid space, and the condylar position at rest would be shifted as a consequence. Our result showed that one year after surgery, when the mandible was at rest position, the condylar position shifted within around 2 mm from its position before surgery. However, in our study, the condylar positional change was only evaluated one year after surgery. Therefore, it was difficult to draw a conclusion on whether the change occurred due to surgery or after the adaptation process over time. Ma RH et al. stated that the condylar position right after surgery changed significantly, then gradually regressed to its original position, but not totally the same. The location change was almost finished six months after surgery.[27] Regardless of the group of patients concerned, whether it was surgery on patients with asymmetry,[10] TMD symptoms,[28] condylar positioning device employed,[29] or orthognathic surgery-first approach,[30] condylar position tended to experience small change (less than 1mm) in the long-term follow-up. We employed Spearman's correlation model to test our hypothesis about the influence of remodeling of TMJ bony structures on the change of the condylar rest position. The remodeling of the glenoid fossa showed no correlation with the change of condylar rest position, condylar remodeling in the anterior region, and superior region showed weak but positive correlations with condyle position anterior-posteriorly. Therefore, we considered that the remodeling of TMJ bony structures did not have a substantial relationship with the change of condylar rest position. Although the non-considerable correlation between condylar position and TMJ bony structures change suggests that our initial hypothesis is not applicable, the condyle did not assume the same rest position as pre-operatively. Therefore, this change should be affected by other factors. Elucidating the factors that influence the position of the condyle after surgery will provide valuable data to integrate into the orthognathic simulation software because, to date, most simulation software assumes that the condyle is a static structure in orthognathic surgery. Our study found that the clinical characteristics of patients before surgery including Wits, overjet and ANB, can be used as prognostic factors of condylar volume reduction after surgery. Despite a slight difference, Wits provided the highest percentage of correct prediction (71.8%). Among intervention factors, only mandibular repositioning correlated with the total condylar volume change. Furthermore, the result of regression analysis corroborated the previous findings that mandibular advancement might trigger the remodeling process.[31] Aside from the clinical characteristics and surgical repositioning of the mandible, many authors contemplated that the change of condylar location might be the risk factor of condylar remodeling. Their results, however, were controversial. Some reported no correlation between remodeling and displacement,[19] and others showed a weak to the moderate relationship.[32, 33]

Concerning the clinical characteristics that had a correlation with the remodeling in different regions of the condyle, in agreement with factors that correlated with the overall volume change, overbite, occlusal plane change and maxillary surgery had no or weak correlation with the remodeling in specific regions. Gomes [33] also pointed out that the mandibular plane angle and overbite might play a minimal role in the remodeling process of the condyle postoperatively. It is noteworthy that although clinical characteristics (Wits, overjet, ANB) and amount of mandibular reposition correlated with the gross volume change, they mainly correlated with the change in the anterior region. Since the posterior region was also the region experiencing the most change in both class II and class III patients, there should be other factors that affect the change in this region. An in vitro simulation of force distribution on the condyle head of Throckmorton et al. demonstrated the pattern of force applied on the condyle, the most tensile strain was found in the anterior region, and the most compressive strain was in the posterior region.[34] It suggested that the different clinical characteristics might have worked through different mechanisms to affect the remodeling process of the condyle.

Surgical movement of the maxilla showed no correlation with glenoid fossa remodeling, but mandibular surgery showed a weak correlation with the remodeling in the lateral region. It is interesting to note that, although overbite revealed no correlation with condylar remodeling, it showed some relationship with the remodeling in the anterior region of the glenoid fossa. Other predictors of the condylar remodeling process including

Wits and overjet presented no correlation with the remodeling of the glenoid surface.

The study's strength was that we included both the condyle and the glenoid fossa in our analysis. Therefore, we could investigate the impact of the remodeling of both structures which constitute the glenoid space on the condylar rest position. However, there were some limitations that should be concerned. First of all, all the analyses were carried out by a single investigator, therefore intra-ratter bias in determining anatomical landmarks cannot be excluded. Moreover, in this research, the clinical data on the skeletal stability of patients postoperatively were not included. Hence, it was impossible to find the threshold of bone resorption that can delineate the physiological and pathological resorption.

5. Conclusion

The ultimate goal of orthognathic surgery is to obtain a long-term stable occlusion postoperatively. Elucidating the post-operative morphological and functional changes in the temporomandibular joint and surrounding soft tissues may help to prevent the problem of the occlusal relapse. Our study was able to analyse the change of both condyle and glenoid fossa as well as their influence on condylar position after surgery in detail with the advanced 3D technique. We found that condylar volume tended to reduce after surgery in class II patients, the opposite tendency was observed in class III patients. Also, although both the condyle and glenoid fossa experienced some morphological changes after surgery, those changes did not show a relevant influence on the change of condylar position. However, considering the importance of condylar position after surgery to surgical stability, future study on the factors that affect the condylar position is necessitated. In addition, our logistic regression model revealed that the advancement of mandible was the risk factor for condylar resorption after surgery. We still do not know the mechanism by which this surgery affects the remodeling process. Perhaps the change of occlusal and musculature force as the result of the change in the mandibular length may play a role. It is, therefore, essential to investigate the status of these structures before and after surgery to clarify this mechanism. We believed that our findings and proposed measurement method will be useful in the future studies of clinical and surgical factors affecting the post-operative stability.

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Table 1. Summarization of patient demographic information and clinical characteristics.

Variable		Class II	Class III	p-value
Number of patients		21	20	
(Total condyle)		(42)	(40)	
Gender				
Male (%)		4(19.05)	7(36.84)	
Female (%)		17(80.95)	13(68.42)	
Age at the surgery (year)		29.35±9.58	28.08±11.20	0.83
CT data collection				
Pre-surgery (day)		25.09±5.85	34.63±12.16	0.06
Post-surgery (year)		23.0±74.61	20.2±6.18	0.31
Overjet (mm)		6.36±2.98	-2.12±4.52	**0.00******
Overbite (mm)		-1.49±5.30	-2.82±3.94	0.37
Cephalometric measurement				
SNA (^{o})	Pre-surgery	83.06±5.59	80.32±3.03	0.83
	Post-surgery	78.89±5.00	80.03±3.29	0.08
SNB (^{o})	Pre-surgery	73.99±5.42	82.07±5.73	0.42
	Post-surgery	73.77±4.73	78.91±3.30	0.41
ANB (^{o})	Pre-surgery	8.70±2.84	-2.55±3.67	**0.00****
	Post-surgery	5.02±2.20	1.55±2.68	**0.00****
Sn-Mp (^{o})	Pre-surgery	48.75±9.33	39.36±10.14	**0.00****
	Post-surgery	50.16±8.70	39.8±10.74	**0.01****
Occ change (^{o})		-1.39±4.56	-0.88±7.81	0.80
Wits appraisal (mm)		1.56±4.39	-13.39±8.48	**0.00****
Range of surgery				
Maxillary (Le Fort I) (mm)[a]		-1.16±3.02	3.29±1.54	**0.00****
Mandible (SSRO) (mm)[b]		1.50±2.67	-5.32±3.61	**0.00****

p: significance. **p≤0.01, independent-samples T-test

Occ change: Change of occlusal plane between T1 and T0

[a,b] Positive value means advancement, a negative value means setback surgery

Table 2. Condylar volume pre-surgery and post-surgery

	Class II	Class III
Pre-surgery (mm^3)	1563.97±517.42	2148.26±435.82
Post-surgery (mm^3)	1521.19±513.02	2194.48±442.12
p-value	**0.003****	**0.003****

**$p<0.01$, paired samples- T-test. Data was presented as Mean ± SD

Table 3. Comparison of the absolute amount of condylar remodeling between class II and class III skeletal malocclusions.

		Medial	Anterior -medial	Anterior -lateral	Lateral	Superior	Posterior -medial	Posterior -lateral
Mean rank	Class II	45.51	38.12	43.61	35.04	44.86	49.14	45.18
	Class III	37.29	45.05	39.29	48.29	37.98	33.48	37.64
Z-score		-1.56	-1.32	-0.82	-2.52	-1.31	-2.31	-1.43
p-value		0.12	0.19	0.41	**0.01****	0.19	**0.00****	0.15

p: significance. $^{**}p \leq 0.01$, Mann-Whitney U test

Table 4. Comparison of the absolute amount of glenoid fossa remodeling between class II and class III patients.

		Medial	Anterior -medial	Anterior -lateral	Lateral	Superior	Posterior -medial	Posterior -lateral
Mean rank	Class III	36.03	37.15	41.55	39.24	36.73	37.25	37.25
	Clas II	44.98	43.85	39.45	41.76	44.28	43.75	43.75
Z-score		-1.72	-1.29	-0.40	-0.49	-1.45	-1.88	-1.25
p-value		0.21	0.06	0.09	0.20	0.69	0.63	0.15

p: significance. Mann-Whitney U test

Table 5. Correlation between remodeling of the condyle and the change of condylar rest position in three axes (Spearman's correlation)

		Medial	Anterior-medial	Anterior-lateral	Lateral	Superior	Posterior-medial	Posterior-lateral
X	r	0.09	0.12	0.07	0.06	0.02	-0.26	-0.13
	p	0.43	0.28	0.54	0.58	0.88	**0.02***	0.23
Y	r	0.18	0.25	0.26	0.08	-0.25	0.03	-0.02
	p	0.10	**0.02***	**0.02***	0.47	**0.02***	0.82	0.84
Z	r	-0.12	-0.01	-0.14	0.16	0.06	-0.12	-0.02
	p	0.27	0.91	0.22	0.16	0.61	0.29	0.83

r: Spearman's correlation coefficient

p: significance. $^*p \leq 0.05$

Table 6. Factors related to the total condylar volume change

Variables	Spearman's correlation		Binary Logistic Regression			
	r	p	B	p	Exp(B)	Correct prediction (%)
MaxSurgery	0.16	0.15				
MandSurgery	-0.27	**0.02***	0.15	**0.01****	1.17	66.70
Wits	-0.37	**0.00****	0.08	**0.00****	1.09	71.80
Overjet	-0.38	**0.00****	0.17	**0.00****	1.19	68.80
Overbite	0.11	0.33				
Occ change	0.04	0.72				
ANB	-0.47	**0.00****	0.18	**0.00****	1.19	69.20

r: Spearman's correlation coefficient

p: significance. **$p \le 0.01$, *$p \le 0.05$

B: regression coefficient. Exp(B): The odds ratio of the condylar volume reduction

Occ change: Change of occlusal plane angle between T1 and T0

MaxSurgery: Range of maxillary surgery

MandSurgery: Range of mandibular surgery

Table 7. Factor related to the remodeling in different regions of interest of the condyle (Spearman's correlation)

	Medial		Anterior-medial		Anterior-lateral		Lateral		Superior		Posterior-medial		Posterior-lateral	
	r	p	r	p	r	p	r	p	R	p	r	p	R	P
MaxSurgery	0.13	0.24	0.16	0.17	0.33	**0.00****	0.10	0.39	-0.11	0.36	0.14	0.22	0.07	0.52
MandSurgery	-0.23	**0.05***	-0.36	**0.00****	-0.54	**0.00****	-0.08	0.47	0.03	0.77	0.10	0.38	0.14	0.21
Wits	-0.25	0.03	-0.33	**0.00****	-0.47	**0.00****	0.34	0.02	0.02	0.88	0.02	0.84	0.03	0.78
Occ change	0.01	0.90	0.19	0.09	0.09	0.43	-0.03	0.80	-0.10	0.36	-0.14	0.22	-0.05	0.66
Overjet	-0.26	**0.02***	-0.33	**0.00****	-0.44	**0.00****	-0.15	0.19	0.09	0.45	-0.05	0.68	0.01	0.95
Overbite	0.02	0.88	0.08	0.49	-0.16	0.15	0.19	0.09	0.06	0.61	0.05	0.67	0.26	**0.02***
ANB	-0.31	**0.01****	-0.33	**0.00****	-0.46	**0.00****	-0.28	**0.01****	0.08	0.48	-0.09	0.45	-0.07	0.56

r: Spearman's correlation coefficient, p: significance. *p≤0.05, **p≤0.01. Occ change: Change of occlusal plane angle between T1 and T0. MaxSurgery: Range of maxillary surgery. MandSurgery: Range of mandibular surgery

Table 8. Factor related to the remodeling in different regions of interest of the glenoid fossa (Spearman's correlation)

	Medial		Anterior-medial		Anterior-lateral		Lateral		Superior		Posterior-medial		Posterior-lateral	
	r	p	r	p	r	p	r	p	r	p	r	p	R	p
MaxSurgery	-0.06	0.60	-0.05	0.65	-0.02	0.87	-0.04	0.72	0.12	0.30	-0.01	0.95	-0.07	0.57
MandSurgery	0.16	0.17	0.07	0.55	-0.08	0.49	-0.25	0.03	-0.19	0.10	0.06	0.59	-0.12	0.30
Wits	0.12	0.31	0.10	0.41	-0.02	0.88	-0.15	0.21	-0.13	0.27	0.08	0.51	-0.10	0.42
Occ change	-0.05	0.68	0.02	0.88	-0.06	0.62	-0.03	0.79	0.00	0.97	-0.05	0.68	0.00	0.98
Overjet	0.12	0.29	0.14	0.24	0.07	0.54	-0.03	0.79	-0.11	0.35	0.05	0.68	-0.06	0.61
Overbite	0.23	**0.04***	0.26	**0.02***	0.22	**0.05***	0.12	0.31	0.18	0.12	0.22	0.06	0.14	0.21
ANB	-0.10	0.37	-0.05	0.67	-0.04	0.72	-0.10	0.40	-0.24	**0.04***	-0.09	0.45	-0.18	0.11

r:Spearman's correlation coefficient, p: significance. *p≤0.05. Occ change: Change of occlusal plane angle between T1 and T0. MaxSurgery: Range of maxillary surgery, MandSurgery: Range of mandibular surgery

Supplementary table 1. Correlation between condylar rest position and glenoid fossa remodeling (Spearman's correlation)

		Medial	Anterior-medial	Anterior-lateral	Lateral	Superior	Posterior-medial	Posterior-lateral
X	r	-0.02	-0.02	-0.01	-0.03	-0.01	0.17	0.09
	p	0.84	0.85	0.95	0.78	0.90	0.13	0.44
Y	r	0.01	-0.07	-0.10	-0.07	0.06	-0.08	-0.02
	p	0.94	0.55	0.38	0.53	0.57	0.50	0.87
Z	r	-0.03	-0.12	-0.19	-0.06	-0.17	-0.04	-0.13
	p	0.83	0.30	0.10	0.62	0.13	0.75	0.26

r: Spearman's correlation coefficient

p: significance.

FIGURES LEGEND

Figure 1. The head orientation process

The head re-orientation process. The Frankfort horizontal plane goes through the superior border of the opening of the bony external auditory meatus and the lowest point on the margin of the right orbit. This plane was reoriented to coincide with the horizontal plane of the 3D slicer (red). The posterior margin of the right external auditory meatus was reoriented to match the coronal plane (green). The facial midline was adjusted to coincide with the sagittal plane (yellow). **A, B,** Before re-orientation-Anterior view and Lateral view respectively; **C, D** After re-orientation-Anterior and Lateral view respectively.

Coordinates: R(red): Right-Left axis; A(green): Anterior-Posterior axis; S(blue): Superior-Inferior axis.

Figure 2. Condylar volume measurement

The shape correspondence process generated pre-surgery (T0) and post-surgery (T1) models with the corresponding points on the surface (**A, B**). The accuracy of the correspondence was verified by Shape Population Viewer Tool. The same color indicates the corresponding regions of T0 and T1 models (**C**). Pre-operative model (yellow) and post-operative model (red) were superimposed using the Procrustes alignment method (**D, E**). The vertical (green) and horizontal (red) cutting planes which go through the lowest point of the sigmoid notch were defined to separate the condylar head from the rest of the mandible (**F**). The volume of the condylar head was recorded (**G**).

Coordinates: R(red): Right-Left axis; A(green): Anterior-Posterior axis; S(blue): Superior-Inferior axis.

Figure 3. Regions of interest of condyle

Regions of interest (ROI) used for quantifying the remodeling in different regions of the condyle. (*Right condyle*)

Coordinates: R(red): Right-Left axis; A(green): Anterior-Posterior axis; S(blue): Superior-Inferior axis.

Figure 4. Regions of interest of glenoid fossa

Regions of interest (ROI) used for quantifying the remodeling in different regions of the glenoid fossa. (*Right glenoid fossa*)

Coordinates: R(red): Right-Left axis; A(green): Anterior-Posterior axis; S(blue): Superior-Inferior axis.

Figure 5. Measurement the change of condylar head position

The change of condylar rest position was the distance between the highest point of T0 and T1 models propagated to three axis X, Y, Z. The X-axis: medial-lateral movement, the Y-axis: antero-posterior movement, the Z-axis: vertical movement.

Figure 6. Quantification of condylar remodeling in regions of interest

Quantification of condylar remodeling in regions of interest. A positive value means new bone formation. A negative value indicates bone resorption.

Figure 7. Quantification of glenoid fossa remodeling in regions of interest

Quantification of glenoid remodeling in regions of interest. A positive value means new bone formation. A negative value indicates bone resorption.

Figure 8. Condylar positional change

Measurement of condylar positional change when mandibular at rest in class II and class III skeletal malocclusions. X-medial-lateral movement, the Y-antero-posterior movement, Z-superior-inferior movement. A positive value means the condyle moves anteriorly, laterally and superiorly.

Supplementary Figure 1. Identifying the center of ROI of the condyle

1, Marking the center points in the ITK-SNAP

This figure Illustrates the process of identifying the center of ROI of the condyle (*right side*) in ITK-Snap software**.** The pre-labelled landmark is signified in dark blue color. **A,** Scroll the computer mouse in the axial plane along the height of the condyle until the last radiopaque image of the condylar head can be seen. Label this point as the top of the condyle (center of the superior region). **B,** Scroll the computer mouse in the sagittal plane along the medial-lateral width of the condyle until the last radiopaque image of the condylar head can be seen on the lateral side. This point is labelled as the lateral pole of the condyle (center of the lateral region). **C,** Similar to B until the last radiopaque image of the condylar head can be seen on the medial pole, label this point as the center of the medial region. **D,** The middle point between the top of the condyle and the axial plane going through the lowest point of the sigmoid notch is marked as point A. In the axial plane, draw the horizontal line which cut the posterior-lateral and posterior-medial margin of the condyle at points B and C respectively. **E,** The intersection between the sagittal plane which goes through the center point of points A and B and the anterior margin of the condyle is labelled as the center of the anterior-lateral region, the intersection with the posterior-lateral margin is labelled as the center of the posterior-lateral region. **F,** Similarly, the intersection between the sagittal plane which goes through the center point of points A and C and the anterior margin of the condyle is labelled as the center of the anterior-medial region. The intersection with the posterior-medial margin is labelled as the center of the posterior-medial region. **G,** Center of anterior-lateral and anterior-medial regions on a 3D model. **H,** Center of posterior-lateral and posterior-medial regions on a 3D model.

2, Superimposing the point-marked model and color-mapped model

The schematic diagram illustrates the color-mapped model (yellow model) merged with the point-marked model (Red model, marked points are denoted in dark blue color) to identify the center of the regions of interest in the condyle.

Coordinates: R(red): Right-Left axis; A(green): Anterior-Posterior axis; S(blue): Superior-Inferior axis.

Supplementary Figure 2. Identifying the center of ROI of the glenoid fossa

1, Marking the center points in the ITK-SNAP

This figure Illustrates the process of identifying the center of ROI of the glenoid fossa (*right side*) in ITK-Snap software**.** The pre-labelled landmark is signified in dark blue color. Firstly, the axial plane going through the lowest point of the articular tubercle is used to determine the lower border of the glenoid fossa. **A**, Scroll the computer mouse along the height of the glenoid fossa until the first radiopaque image can be seen. This is marked as the highest point of the glenoid fossa. In the corresponding coronal plane, identify the center point between the highest point of the glenoid fossa and the axial plane going through the lateral border of the glenoid fossa (point A). The center point between the highest point of the glenoid fossa and the axial plane going through the medial border of the glenoid fossa is marked as point B. The center point between the lowest point of the lateral border and the sagittal plane going through the highest point of the glenoid fossa is marked as point C. The center point between the lowest point of the medial border and the sagittal plane going through the highest point of the glenoid fossa is marked as point D. **B,** The axial plane going through point A intersects with the lateral surface of the glenoid fossa at the center of the lateral region. The axial plane going through point B intersects with the medial surface of the glenoid fossa at the center of the medial region. **C,** The intersection of an axial plane going through point A, the sagittal plane going through point C and the anterior surface of the glenoid fossa is labelled as the center of anterior-lateral region, and the intersection with the posterior surface of the glenoid fossa is labelled as center of posterior-lateral region. **D,** The intersection of an axial plane going through point A, the sagittal plane going through point D and the anterior surface of the glenoid fossa is labelled as the center of the anterior-medial region, and the intersection with the posterior surface of the glenoid fossa is labelled as center of posterior-medial region.

2, Superimposing the point-marked model and color-mapped model

The schematic diagram illustrates the color-mapped model (yellow model) merged with the point-marked model (Red model, marked points are denoted in dark blue color) to identify the center of the regions of interest in the condyle.

Coordinates: R(red): Right-Left axis; A(green): Anterior-Posterior axis; S(blue): Superior-

Inferior axis.

Figure 1. The head orientation process

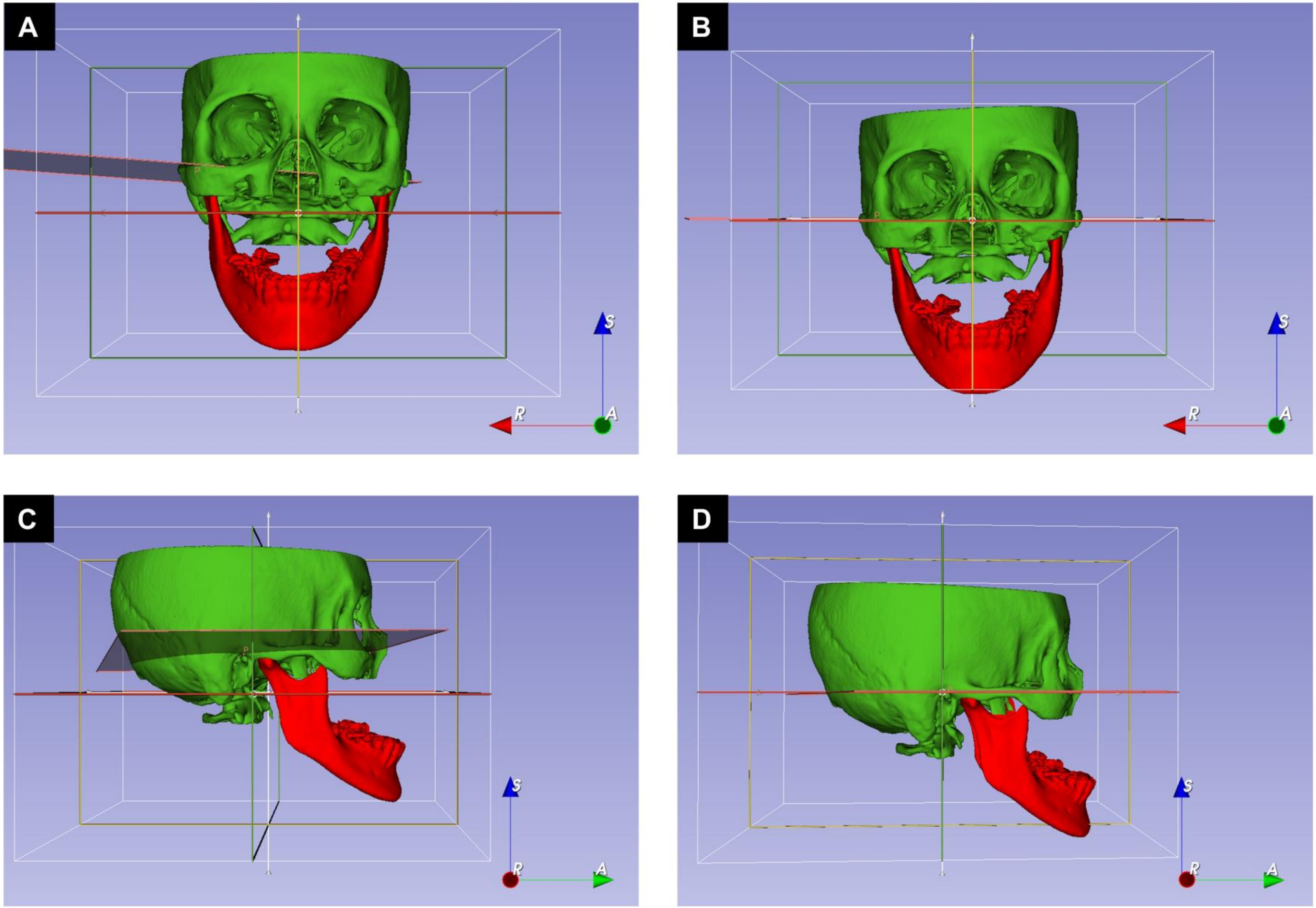
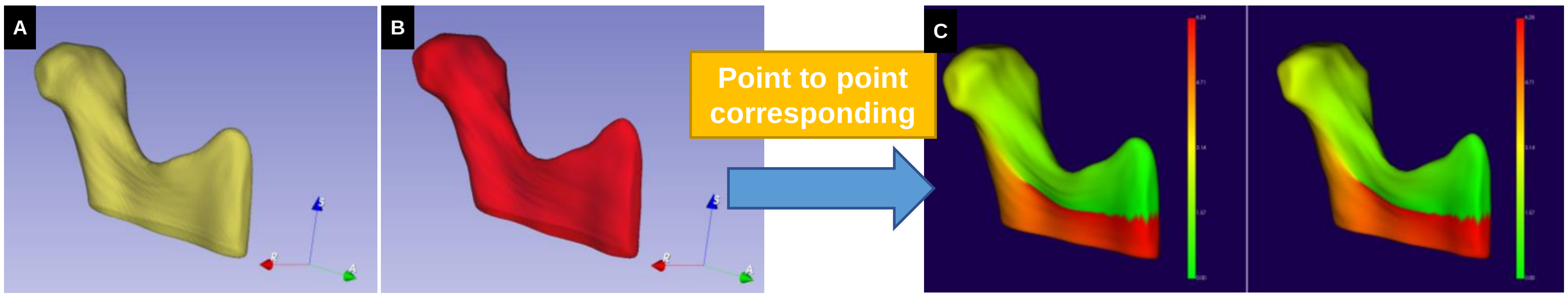


Figure 2. Condylar volume measurement

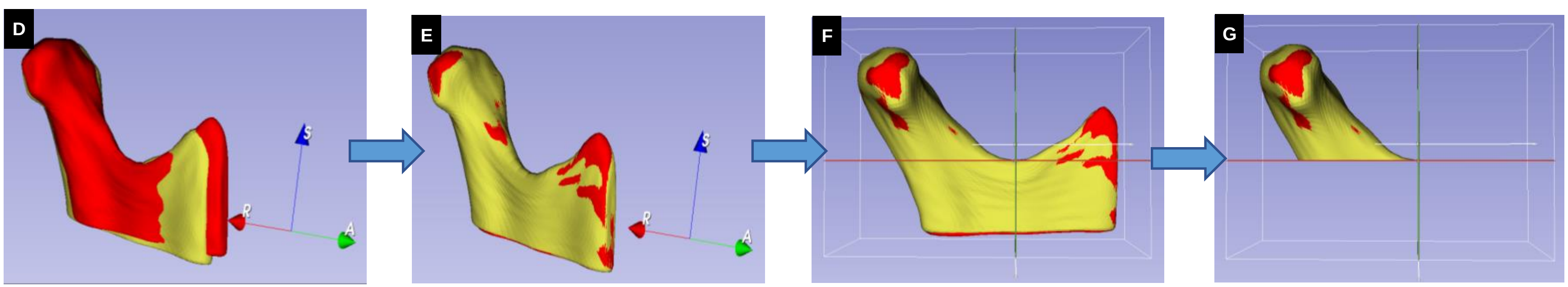
1. Generating the corresponding models of T0 and T1



T0 model T1 model

Same color regions: corresponding regions

2. Defining the borderline to measure condylar volume



Before alignment | After alignment | Define cutting plane | Condylar head

Pre-surgery model (yellow) Post-surgery model (red)

Figure 3. Regions of interest of condyle

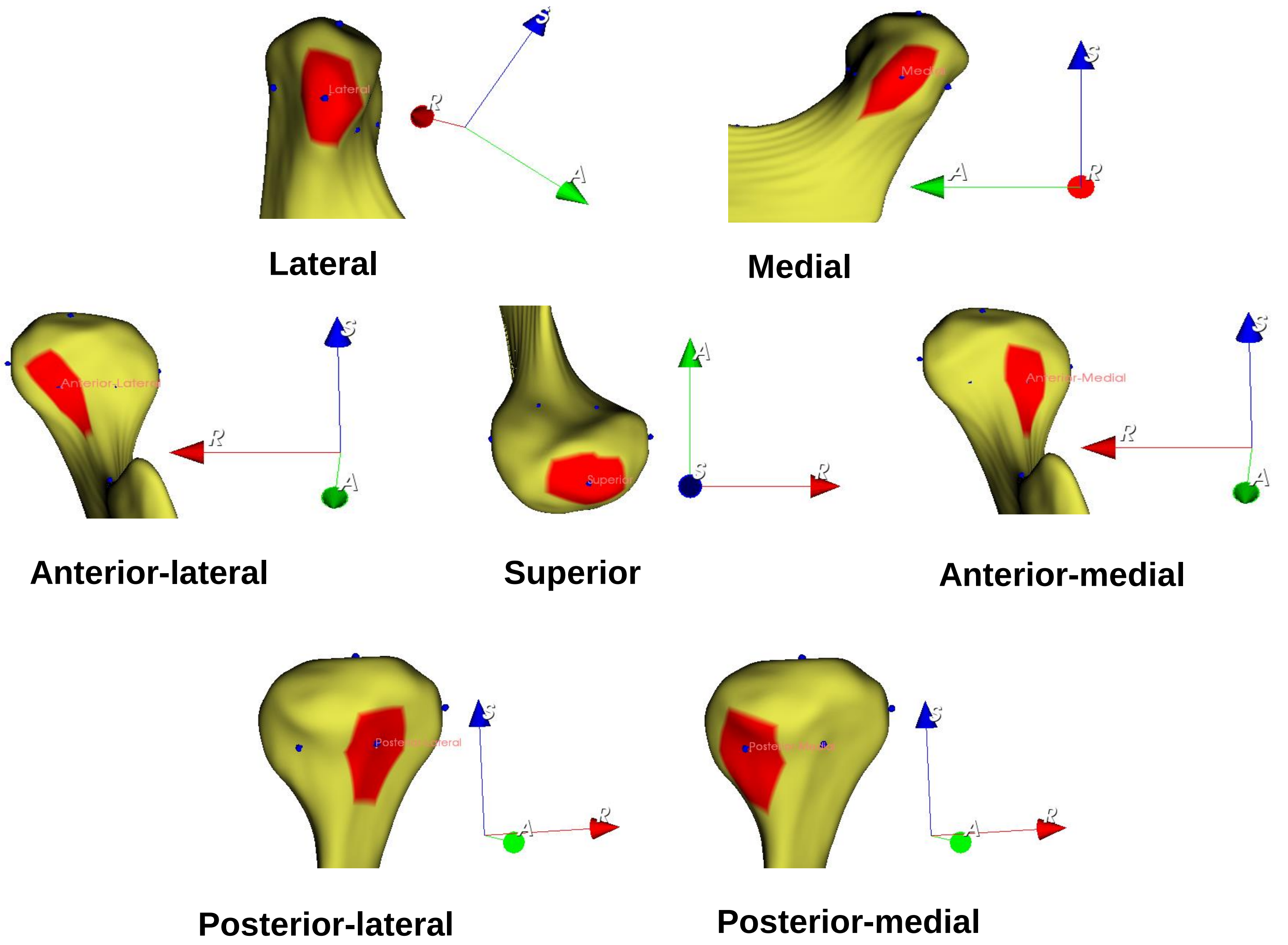


Figure 4. Regions of interest of glenoid fossa

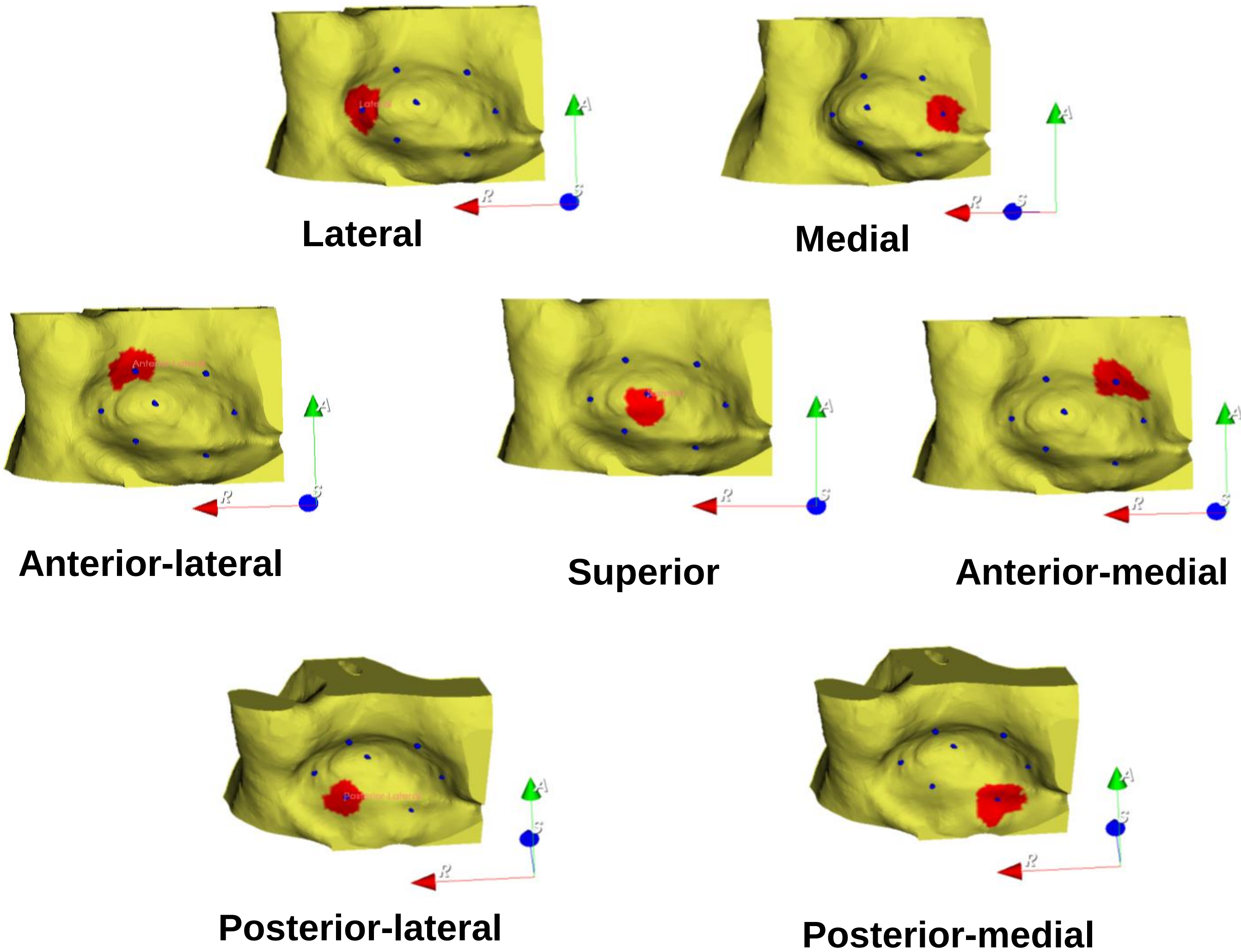
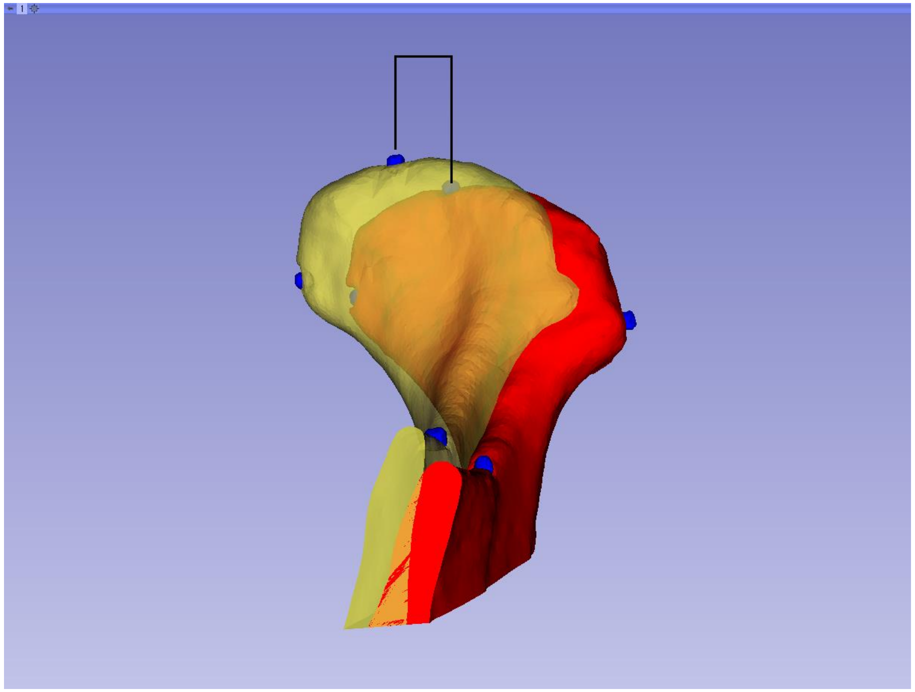
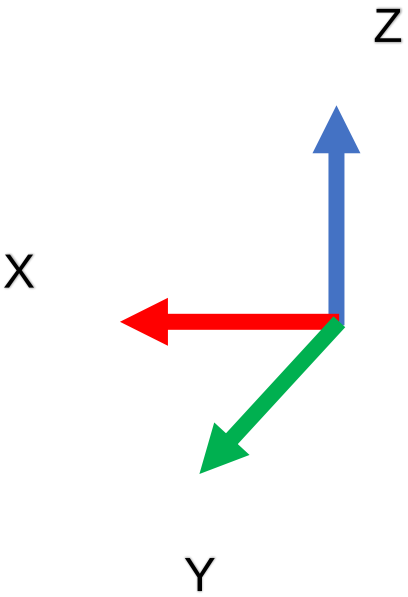


Figure 5. Measurement the change of condylar head position





T0 T1 Pre-marked landmark

Figure 6: Quantification of condylar remodeling in regions of interest

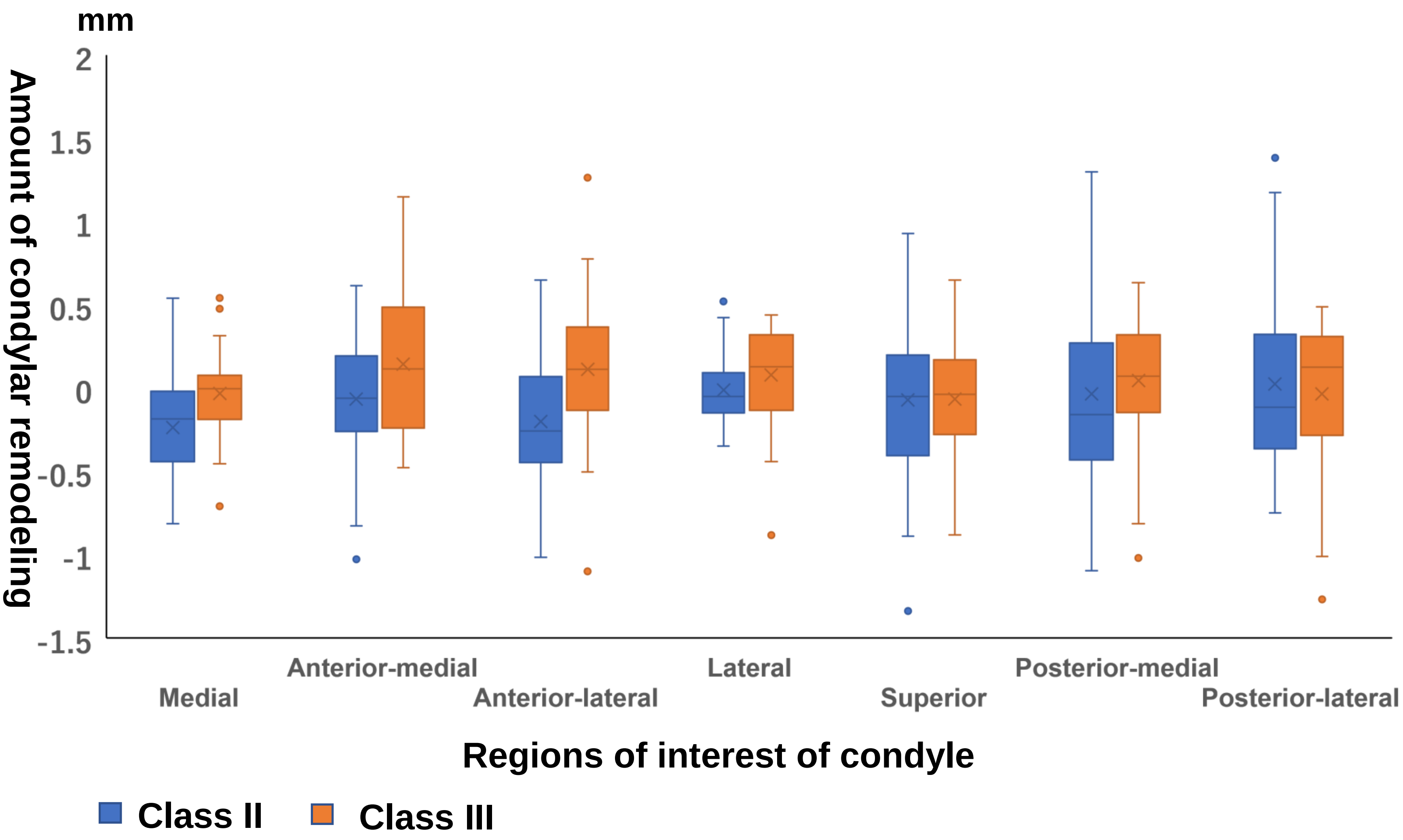


Figure 7: Quantification of glenoid fossa remodeling in regions of interest

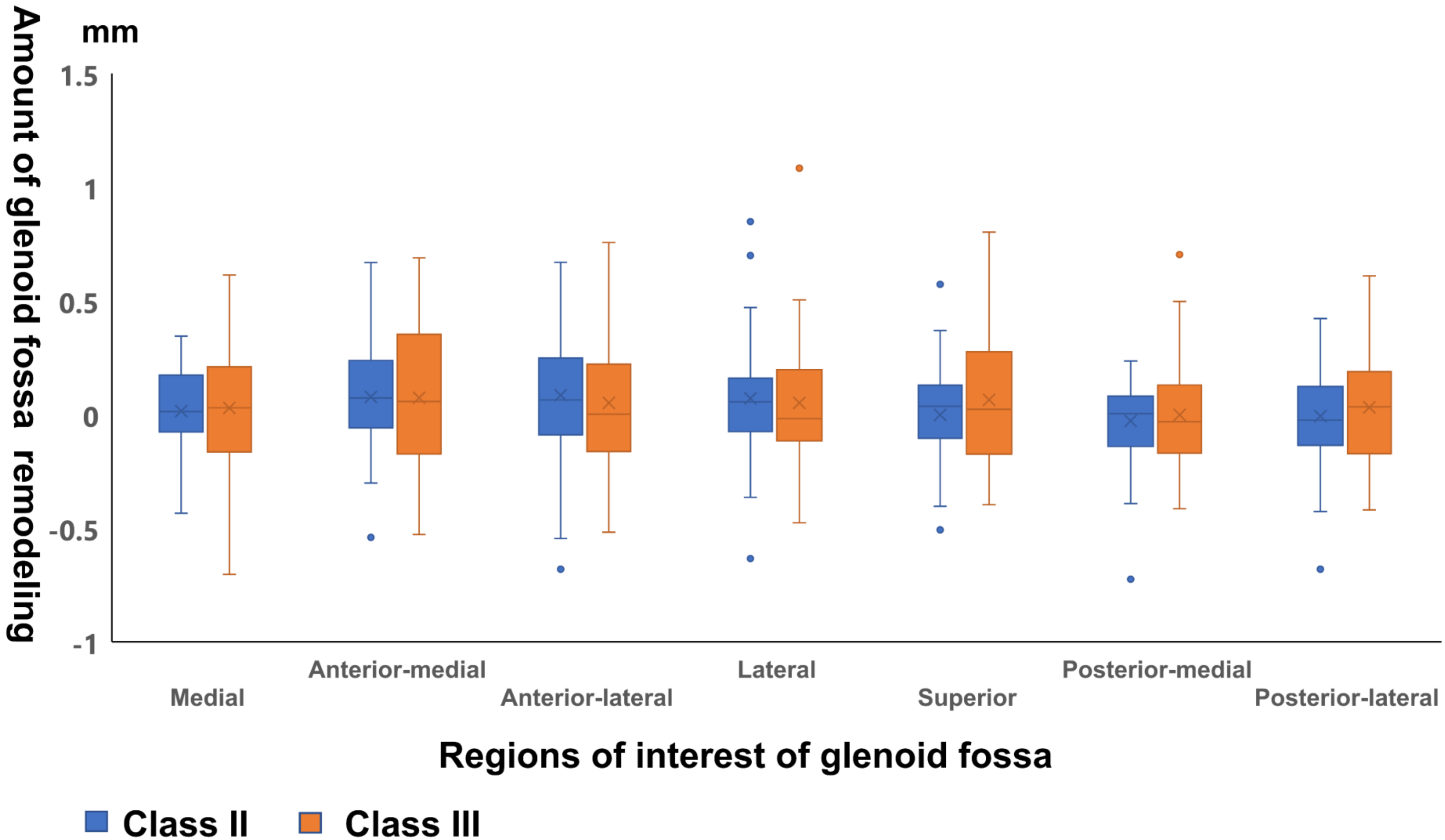
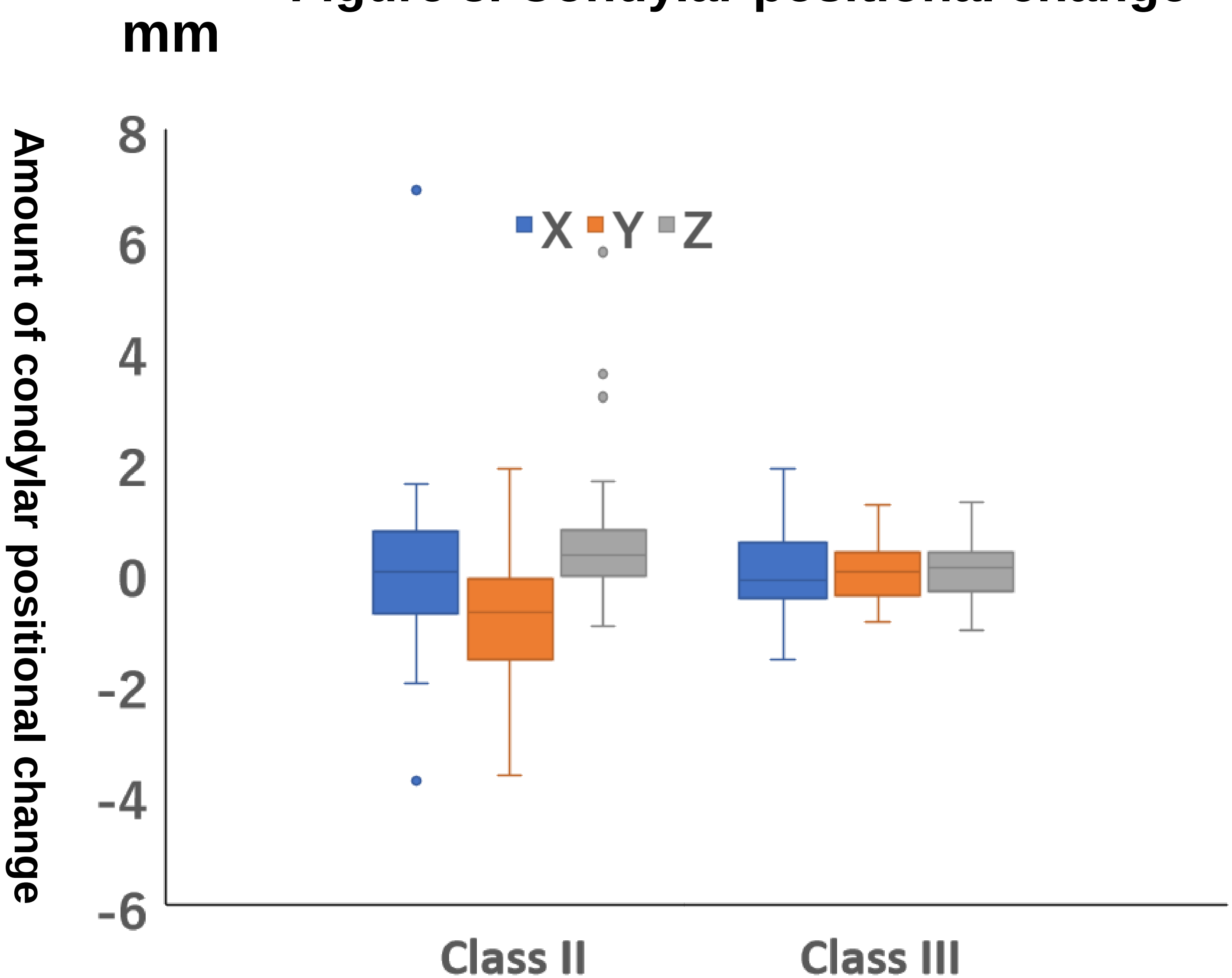
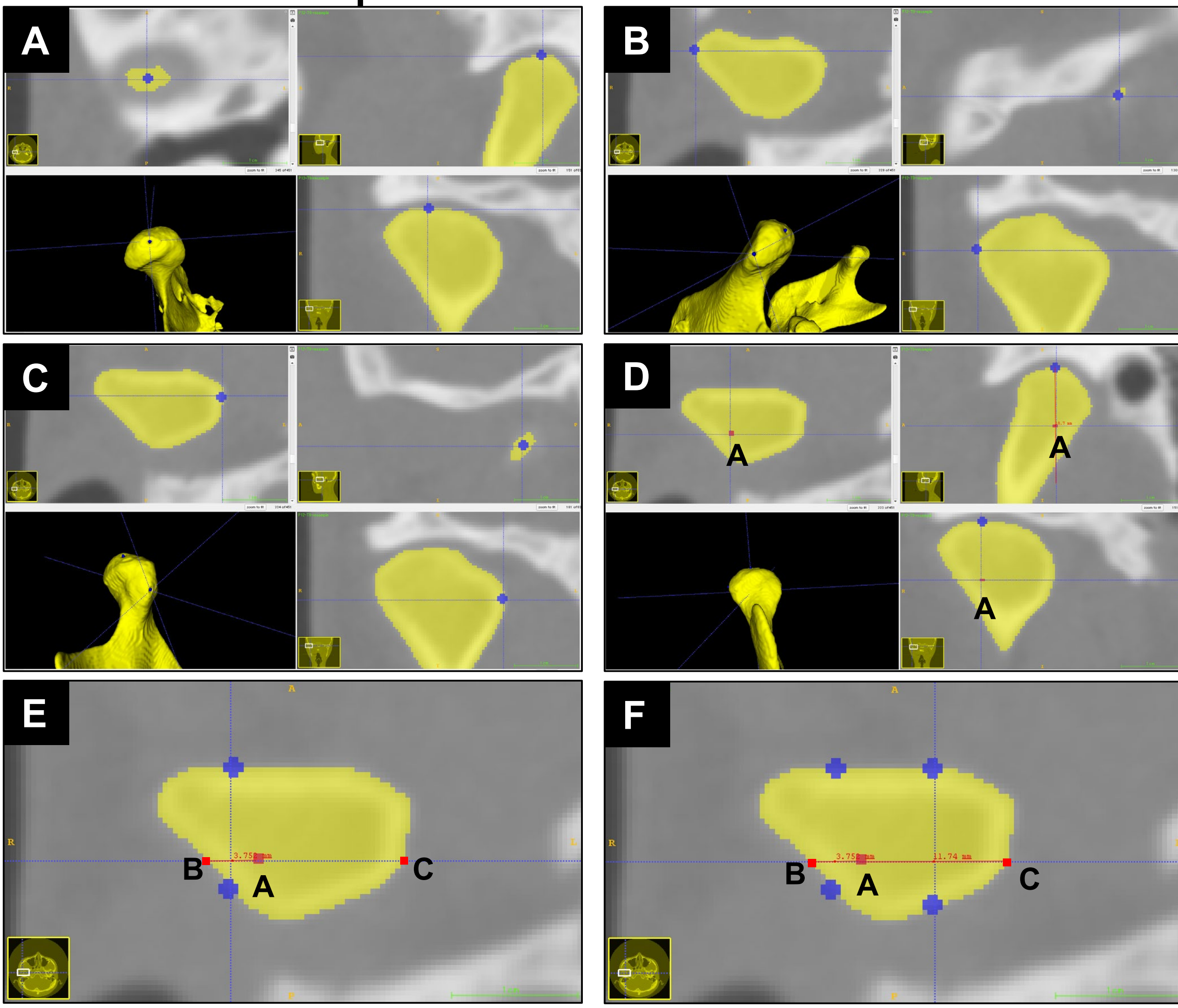


Figure 8. Condylar positional change

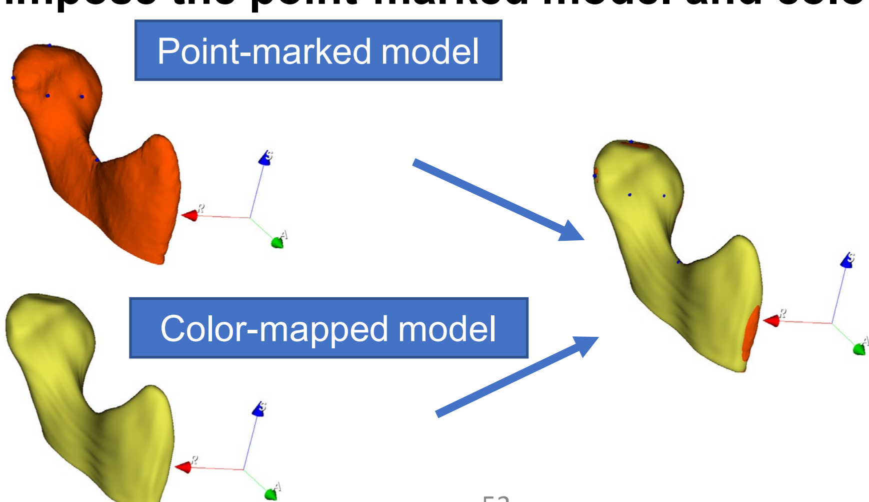


Supplementary Figure 1. Identifying the center of ROI of the condyle

1. Mark the center points in the ITK-SNAP

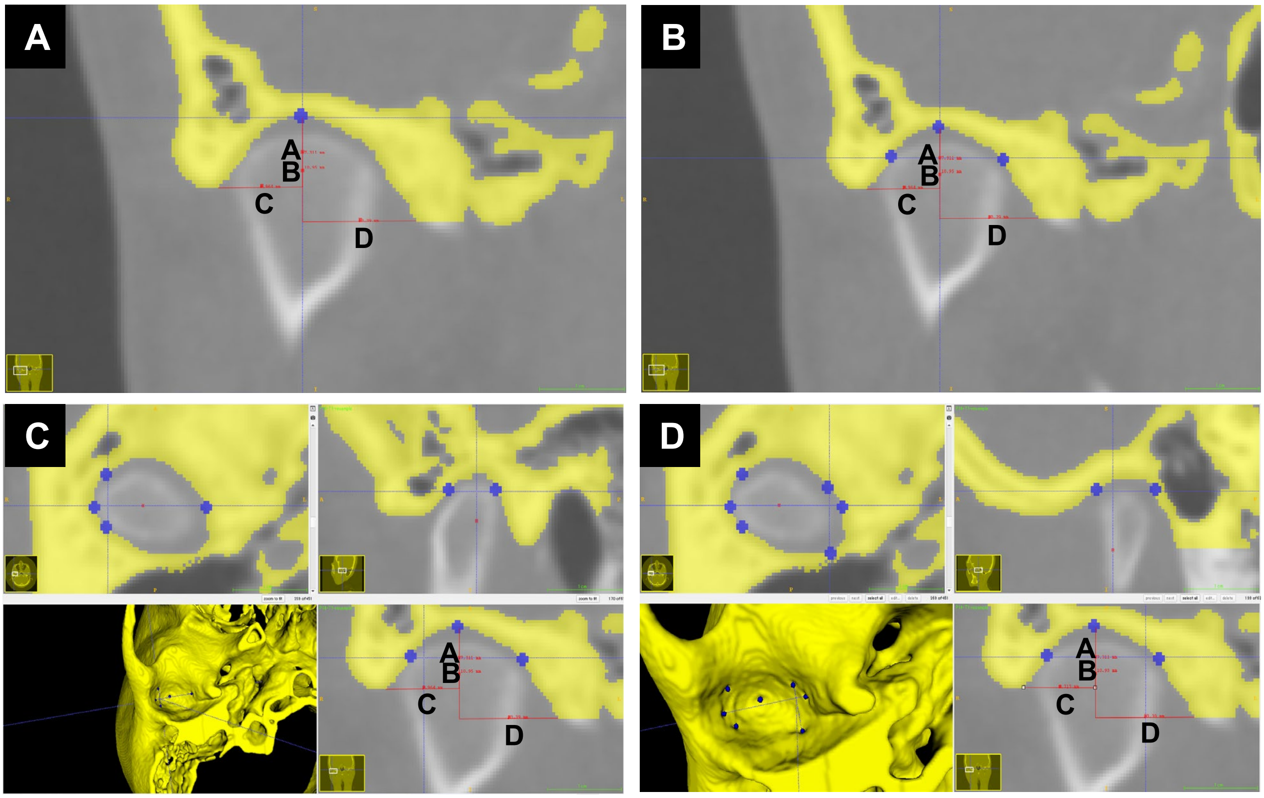


2. Superimpose the point-marked model and color-mapped model



Supplementary Figure 2. Identifying the center of ROI of the glenoid fossa

1. Mark the center points in the ITK-SNAP



2. Superimpose the point-marked model and color-mapped model