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The influence of bilateral sagittal split ramus osteotomy on the stress distributions in the temporomandibular joints of the patients with facial asymmetry under symmetric occlusions

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Abstract

The aim of this study is to compare the differences in the stress distributions in the temporomandibular joints (TMJs) of the patients with facial asymmetry before and after bilateral sagittal split ramus osteotomy (BSSRO) under the symmetric occlusions using the three-dimensional (3D) finite element method.

Ten facial asymmetry patients (Preoperative group, age 24.6±4.8 years) and 10 asymptomatic subjects (Control group, age 26.8±4.9 years) were recruited. After the patients underwent BSSRO, they were further assigned as the Postoperative group. 3D geometries of the finite element models of the mandible, disc, maxilla, and teeth were reconstructed according to cone-beam computed tomography (CBCT) image data. Contact elements were used to simulate the interaction of the disc-condyle, disc-temporal bone, and upper-lower dentition. The muscle forces and boundary conditions corresponding to the central and anterior occlusions were applied on the models of the 3 groups. The finite element models were validated with experimental data showing the accuracy of the simulation results.

The simulation predicted preoperative significant differences of stresses between non-deviated sides and deviated sides were disappeared after the surgery under the central and anterior occlusions ($P < .05$). Almost all stresses in the patient models had significantly decreased after BSSRO, leveling it to the stress values of the normal subjects. Moreover, the simulation results coincided with the clinical cases which showed that BSSRO had helped to release or remove the signs and symptoms of temporomandibular disorders (TMD).

In conclusion, BSSRO could correct the asymmetric stress distributions of TMJs and decrease the magnitude of the stresses for the patients with facial asymmetry. Those decreases also associated with the recovery of TMD.

Abbreviations: 2D = two-dimensional, 3D = three-dimensional, AD = anterior digastric, AT = anterior temporalis, BSSRO = bilateral sagittal split ramus osteotomy, CBCT = cone-beam computed tomography, DICOM= Digital Imaging and Communications in Medicine, DM = deep masseter, DOF = degrees of freedom, ILP = inferior lateral pterygoid, MP = medial pterygoid, MT = middle temporalis, PT = posterior temporalis, SLP = superior lateral pterygoid, SM = superficial masseter, TMD = temporomandibular disorder, TMJ = temporomandibular joint.

Keywords: bilateral sagittal split ramus osteotomy, biomechanics, finite element method, stress distributions, temporomandibular disorders, temporomandibular joint

1. Introduction

Facial asymmetry is a common jaw deformity with an incidence ranging from 8.7% to 23.3%.[1,2] Previous studies reported that joint pain, abnormal sound, disc displacement, and abnormal jaw movements are often found in the patients with facial asymmetry.[3–6] Signs and symptoms of temporomandibular disorder (TMD) are caused by the differences existed in the mandibles, condyles, and discs. Bilateral sagittal split ramus osteotomy introduced by Trauner and Obwegeser[7] has usually been used to correct facial asymmetry. However, several disadvantages, such as fracture, bleeding, infection, and TMD, were found after bilateral sagittal split ramus osteotomy (BSSRO).[8,9] Some of these disadvantages were associated with the changes of stress in temporomandibular joint (TMJ) after osteotomy.[10] Biomechanically, these changes about the patients with facial asymmetry after BSSRO would affect the stress distributions within the TMJ. Thus, biomechanical research about the stresses of TMJ was a crucial way to get a better understanding about BSSRO.

The clinical effects of BSSRO on TMJ in previous studies remained controversial.[11–15] Some researchers found that BSSRO could cause anterior disc displacement or other symptoms of TMD.[16,17] The opposite viewpoint indicated the

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ability of BSSRO to relieve the signs and symptoms of TMD and to improve TMJ functions.[12,13] However, the conclusions from several studies illuminated that BSSRO made little contribution to the anterior disc displacement, condylar resorption, and other symptoms of TMD.[17,18] Hence, a better understanding of the influence of BSSRO on TMJ and the association of TMD and BSSRO was necessary to be evaluated.

Previous studies mainly focused on the changes of TMJ morphology and position after surgery.[13,14] The influence of BSSRO on TMJ biomechanics is unclear. Thus, the purpose of this study is to elucidate the changes of the stress distributions in TMJs after BSSRO for the patients with facial asymmetry under symmetric loads.

2. Materials and methods

2.1. Subjects and data acquisition

A total of 20 individuals were involved in this study, including 10 asymptomatic subjects (4 women and 6 men, 26.7±4.8 years old), assigned as the Control group, and 10 patients (5 women and 5 men, 24.6±4.8 years old) diagnosed with facial asymmetry (Preoperative group). After all the patients underwent BSSRO, they were further assigned as the Postoperative group. All the patients were consecutively recruited from the Affiliated Hospital of Stomatology of Chongqing Medical University between January 2014 and January 2016. They were clinically examined by a maxillofacial surgeon according to the diagnostic criteria guidelines. The inclusion criteria of the patients with facial asymmetry were as follows: the patients must be at least 18 years old; the deviations from the facial midline were >5 mm (Fig. 1); and no prior TMJ-related procedures. After surgery, all the patients were followed up for more than half a year. This study was approved by the Affiliated Hospital of Stomatology of Chongqing Medical University Institutional Review Board. All participants had signed an informed consent agreement.

According to the study of Ueki et al[4] mandibular deviation to the left and right were defined as the mandibular midline on the left side and the right side of the facial midline, respectively (Fig. 1). The right side was assigned as the deviation side and the non-deviation side while the left side was assigned as the non-deviation side and the deviation side. In this study, there were 8 patients with mandibular deviation to the left and 2 patients with mandibular deviation to the right.

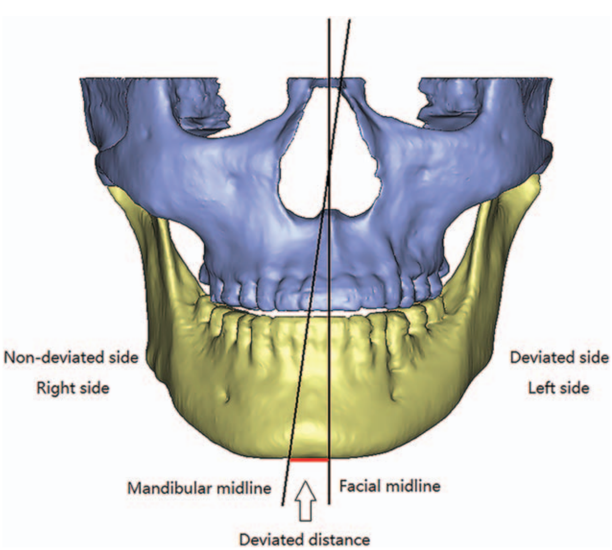

Figure 1. Facial midline and mandibular midline in the frontal view of patients with mandibular deviation to the right. The red line between facial and mandibular midlines indicated the deviated distance, which were >5 mm in the recruited Preoperative group.

The clinical case records for the 10 patients showed 7 patients with preoperative TMD symptoms, including TMJ clicking (7 patients), joint pain (5 patients), and the incongruous bilateral joint movement (6 patients) and 3 of them with postoperative TMD symptoms, including TMJ clicking (3 patients) and joint pain (1 patient). Meanwhile, no preoperative and postoperative TMD symptoms were observed for the remaining 3 patients.

The maxilla and mandible were scanned using a cone-beam computed tomography (CBCT) machine (KaVo 3D eXam, Germany) with a complete head view for all the patients before and 6 months after BSSRO and the asymptomatic subjects. All images were taken following a standardized protocol for patient positioning and exposure parameter settings (120 kVp, 3–8 mA, 20 seconds). The resolution of cross-sectional images was 400 × 400 pixels with the pixel size of 0.4 mm. Each CBCT scan consisted of 290 to 340 images with slice thicknesses of 0.4 mm. The CBCT data were reformatted into Digital Imaging and Communications in Medicine (DICOM) format.

2.2. 3D modeling

The DICOM files were imported into MIMICS (Materialise, Leuven, Belgium) for 3D geometry reconstruction. The boundaries of the maxilla, mandible, and teeth were accurately distinguished on each slice of CBCT. Subsequently, the 3D models were constructed. The articular discs were established according to the anatomical characteristics and the shape of the articular surfaces. The maximum and minimum thicknesses of the disc were located at the posterior band (2–3 mm) and the intermediate zone (approximately 1 mm), respectively. The 3D outer shapes of the mandible, maxilla, and disc were generated using a surface triangulation technique and imported into the finite element software ABAQUS (Dassault SIMULIA, RI) for the generation of the 3D finite element models.

According to previous finite element studies,[19,20] the interaction of the disc-condyle, disc-temporal bone, and upper-lower dentition was considered as contact with a frictional coefficient of 0.001. The Young modulus of the models was assigned based on relevant empirical formulas (Equations (1)–(3)).[21–24] This method could simulate the inhomogeneous material properties of the models. With reference to previous studies,[19,20,25,26] Poisson ratio of the cortical bone, cancellous bone, and teeth was defined as 0.3 while the Poisson ratio of the disc was defined as 0.4. The modified 10-node quadratic tetrahedron element (C3D10M) was used in the contact regions. The 4-node linear tetrahedron element (C3D4) was used for the other regions of the models. The total numbers of nodes and elements for all the models were about 100,000 and 210,000, respectively.

$$GV = HU + 1024 \tag{1}$$

$$\text{Density} = -13.4 + 1017 \times GV \tag{2}$$

$$E = -388.8 + 5925 \times \text{Density} \tag{3}$$

where GV is the gray value, HU is the Hounsfield units, E is Young modulus, and all parameters were adopted using international system units.

2.3. Loading and boundary condition

It is known that the asymmetric oral structure always contributed to the abnormal masticatory function. Thus, symmetric loads such as central and anterior occlusions were used in the study for analyzing the influence of BSSRO on the TMJs.[27] The same loading conditions of the central occlusion and the anterior occlusion were applied to all the models. The superficial masseter (SM), deep masseter (DM), medial pterygoid (MP), anterior temporalis (AT), middle temporalis (MT), posterior temporalis (PT), inferior lateral pterygoid (ILP), superior lateral pterygoid (SLP), and anterior digastric (AD) muscles were considered in this study.[28–30] The 6 degrees of freedom (DOF) of the top surface of maxilla were fully constrained.

2.4. Statistical analysis

The stress parameters of the TMJs were analyzed for each group in order to investigate the biomechanical effects of BSSRO on the TMJs. In addition, the following comparisons were performed: between the Preoperative and Postoperative groups by paired-samples t test, between the deviated and non-deviated sides in the Postoperative group by paired-samples t test, between the Postoperative and Control groups by independent-samples t test. The statistical significance was achieved when $P < .05$. SPSS 20.0 (SPSS Inc, Chicago, IL) was used for the statistical analysis.

3. Results

The preoperative significant differences of the stresses between the non-deviated and deviated sides of the TMJs disappeared after BSSRO ($P < .05$) under symmetric occlusions. Likewise, there were no significant differences of the stresses in the Control group between the left and right sides of the discs, condyles, and temporal bones. Therefore, the magnitudes of all the parameters of the Control group were the average of both sides (presented in Figs. 2–4).

The stresses of TMJs in the Postoperative group were significantly lower than those in the Preoperative group under the central occlusion, and not significantly different from those in the Control group. Furthermore, under the anterior occlusion, the stresses in the Postoperative group were significantly lower than the Preoperative groups. The differences of contact stress at disc and condyle were also observed between the Postoperative group at the non-deviated side and the Control group. In addition, the Postoperative group had significantly higher contact stress from the Control group for the disc at deviated side (Fig. 2). Other parameters of TMJ under the anterior occlusion had no significant difference between the Postoperative group and the Control group.

4. Discussion

Previous studies had determined many aspects of the biomechanical changes after BSSRO. The muscle forces and bite forces were used to assess static and dynamic load variation of condyle after BSSRO.[17] The two-dimensional (2D) rigid body spring model was used to determine the stress distribution on the condyle after BSSRO. The results showed significant differences in stress and displacement distributions between postoperative patients and asymptomatic subjects.[10] The above studies were limited on 2D models. In addition, the 3D finite element method was used to investigate the stress distribution of the closing and opening muscle groups of the jaw after BSSRO.[31] The results indicated that the significant differences of stress distributions between the patients with mandibular prognathism and healthy subjects had disappeared after BSSRO. However, these studies only considered the force or stress distributions of condyles. The articular discs and temporal bones were also essentially crucial in the analysis of the stress distribution in TMJs because the complete TMJ structures should be provided to obtain the interactions. Both the abnormal disc and temporal bone would always

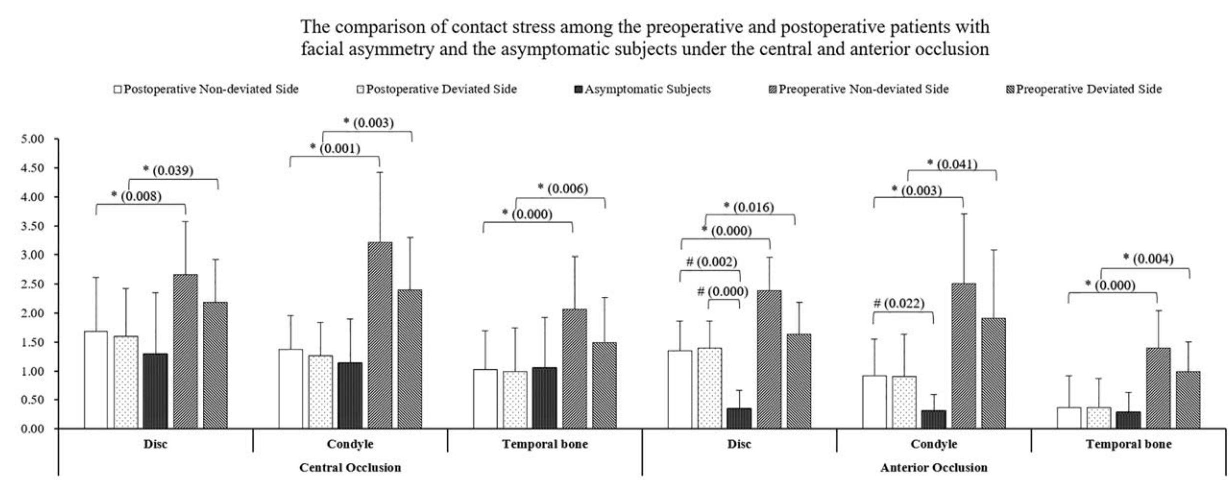

Figure 2. The comparisons of the peak contact stress among asymptomatic subjects, preoperative patients, and postoperative patients with facial asymmetry at both non-deviated side and deviated side under the central and anterior occlusion (MPa). *(P value). Statistically significant difference between non-deviated or deviated side for preoperative and postoperative patients by paired-samples t test ($P < .05$). # (P value) Statistically significant difference between non-deviated or deviated side for postoperative patients and asymptomatic subjects by independent-samples t test ($P < .05$).

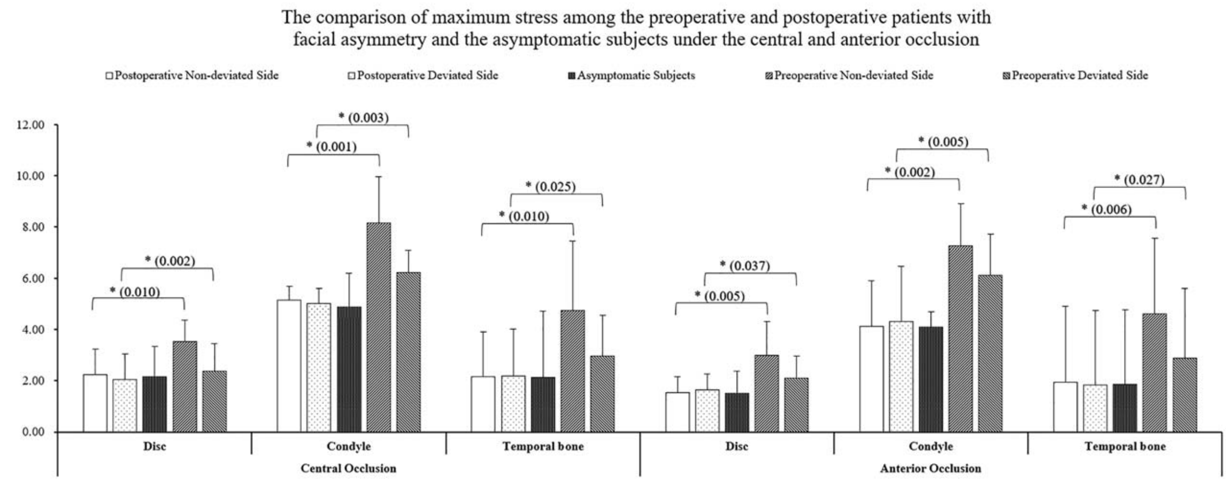

Figure 3. The comparisons of the peak maximum principal stress among asymptomatic subjects, preoperative patients, and postoperative patients with facial asymmetry at both non-deviated side and deviated side under the central and anterior occlusion (MPa). * (*P* value) Statistically significant difference between non-deviated or deviated side for preoperative and postoperative patients by paired-samples *t* test ($P < .05$). # (*P* value) Statistically significant difference between non-deviated or deviated side for postoperative patients and asymptomatic subjects by independent-samples *t* test ($P < .05$).

independently be associated with different kinds of TMDs. Temporal osteoarthritis was associated with the stress distributions of the temporal bone all the time while disc perforation and joint pain were consistently considered to relate to the stress distributions of the articular disc.

According to previous studies, the TMJ morphology would change after BSSRO.[11] However, the biomechanical effects, especially the stress distributions of TMJs about patients with facial asymmetry after BSSRO are still not clear. Therefore, the changes of the stress distributions of the patients with facial asymmetry after BSSRO were analyzed in this study. In addition to the central occlusion, whose importance of oral function was described in previous studies,[25,32] the anterior occlusion was also used as symmetric occlusions to obtain the stress distributions in this study.

The mandibles, maxillae, and discs were used to be considered as homogeneous materials,[25,31] which were inaccurate to simulate the inhomogeneous structures. In this study, the relevant empirical formulas (Equations (1)–(3)) based on Hounsfield units were chosen for the assignment of the Young's modulus values.

4.1. Validation of the finite element models

In this study, contact was illustrated to provide a reasonable simulation for interaction between the disc and the temporal bone and between the disc and the condyle. Five 3D printing experiments in Zhang's study[27] were used to valid the method. Five loadings of 100, 150, 200, 250, and 300 N were applied to the 3D printing models simulating the central occlusion. Ten strain rosettes were mounted on the 3D printed models and 20

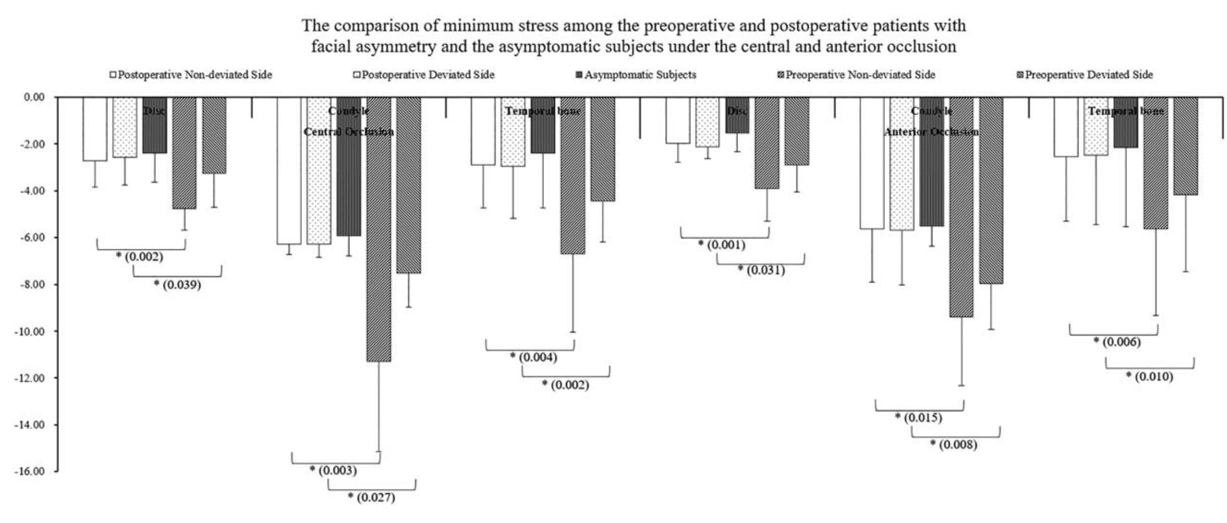

Figure 4. The comparisons of the peak minimum principal stress among asymptomatic subjects, preoperative patients, and postoperative patients with facial asymmetry at both non-deviated side and deviated side under the central and anterior occlusion (MPa). * (*P* value) Statistically significant difference between non-deviated or deviated side for preoperative and postoperative patients by paired-samples *t* test ($P < .05$). # (*P* value) Statistically significant difference between non-deviated or deviated side for postoperative patients and asymptomatic subjects by independent-samples *t* test ($P < .05$).

strain data were recorded. The finite element models and the 3D printing experimental models shared the same geometry, material properties, load, and boundary conditions. The maximum differences of all strain data between the measured strain (from 3D printing models) and predicted strain (from finite element models) were only 5%. Thus, the interactions between discs and temporal bones and between discs and condyles for finite element simulation in this study were reasonable.

4.2. Improvement of asymmetric stress distribution

The stresses of TMJs for asymptomatic subjects had no significant differences between both sides. On the contrary, the preoperative patients with facial asymmetry led to the asymmetry of stress distributions between non-deviated and deviated sides. After the surgery, the asymmetric stress distributions disappeared (Fig. 5). From the follow up of the patients, 6 patients with preoperatively incongruous bilateral joint movement completely recovered after BSSRO. Moreover, it was obvious that the greatest stresses occurred at the non-deviated side in the Preoperative group, as shown in Figs. 2–4. The dramatically high stresses made the signs and symptoms of TMD more likely to occur at non-deviated sides, consistent with the clinical case where only 1 patient with the symptom of TMD at deviated side. Furthermore, the decrease of the maximum principal stress in the discs, condyles, and temporal bones after BSSRO under the 2 occlusions ranged from 35% to 55% on the non-deviated sides and from 10% to 30% on the deviated sides. The decreases of the contact stress and minimum principal stress on the non-deviated side were also greater than those on the deviated side under the 2 occlusions. Both the simulated results and clinical cases suggested BSSRO could improve the asymmetric stress distributions, especially reducing the stresses at the non-deviated sides in accordance with the previous study by Qi et al.[31] Thus, the patients with TMD but without serious maxillofacial deformity could recover by changing the biomechanical environment of TMJs.

4.3. Effects on the stress distributions and the peak stresses

The morphologic changes of TMJ with facial asymmetry were the possible factors leading to abnormal stress distributions. The contact stresses of the disc, condyle, and temporal bone in the preoperative patients were much greater than that of the asymptomatic subjects at both sides. After BSSRO, the average contact stresses in the high stress region of the discs at the non-deviated side and the deviated side under the central occlusion were decreased to 1.68 and 1.60 MPa, comparing to the preoperative 2.66 and 2.19 MPa, respectively. The average contact stress of the discs in the asymptomatic subjects was 1.29 MPa. The average contact stresses of condyle and temporal bone also had different extent of decreases after the surgery (Fig. 2). The increased contact stresses of TMJs would probably lead to joint pain and clicking, but the postoperative stresses that had reduced to normal level could be helpful to alleviate joint pain and clicking. In the clinical cases, 4 of 5 patients with preoperative joint pain and 4 of 7 patients with preoperative clicking were recovered after BSSRO, and the symptoms of joint pain or clicking for the rest of the patients became mild. In addition, the contact stresses of TMJs had no statistical differences between the Postoperative and Control groups. However, although the contact stresses of TMJs at non-deviated side in the Postoperative group were also significantly lower than those of the Preoperative group under the anterior occlusion, there were significant differences of contact stresses at the discs and condyles between the non-deviated side of the Postoperative group and the Control group. It was clear that BSSRO could improve the interaction between the discs and the articular skeleton under the central occlusion but not significant under the anterior occlusion. The disc under the anterior occlusion may sustain more squeezing from the condyle and temporal bone compared with the central occlusion. Therefore, the symptoms of TMD may occur under the anterior occlusion. In the clinical cases of the 7 patients who exhibited preoperative TMD symptoms, 1

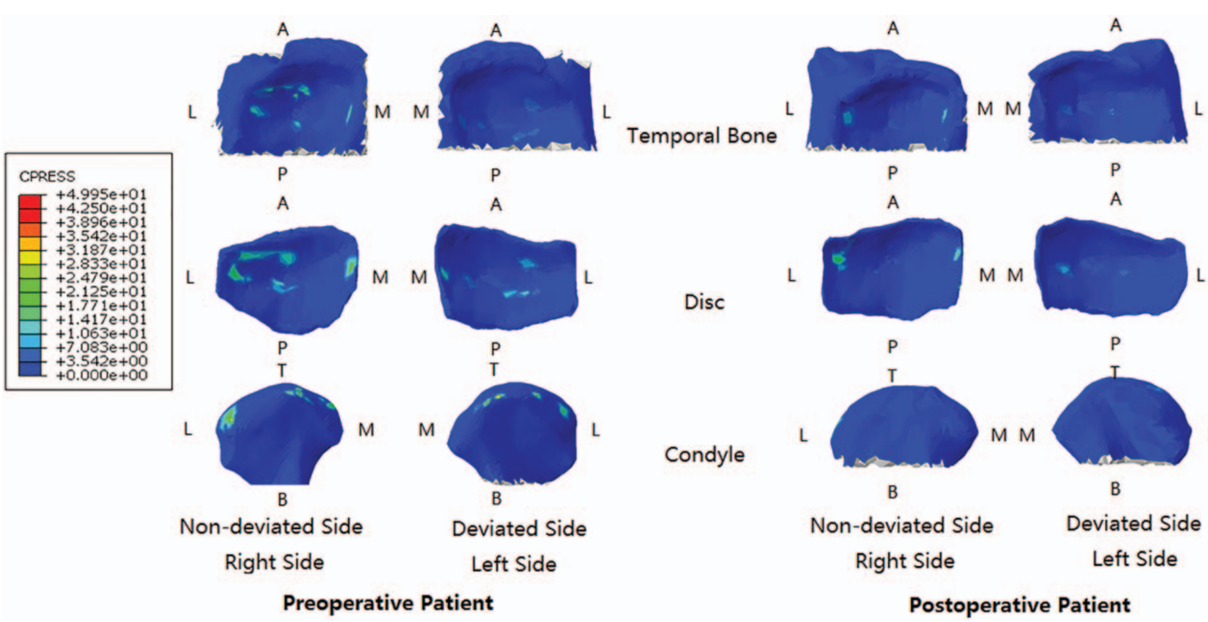

Figure 5. The contact stress distributions of the temporal bones, the discs, and the condyles of a patient with mandibular deviation to the left preoperatively and postoperatively under the central occlusion. A=anterior; B=bottom; L=lateral; M=medial; P=posterior; T=top.

patient experienced joint pain and clicking, 2 patients with clicking, and 4 patients with no postoperative TMD after BSSRO. It was only 26% decrease of contact stress at non-deviated disc for the patient with postoperative joint pain and clicking, compared with 40% and 54% decrease for the 2 patients with postoperative clicking and from 38% to 96% decrease in others with no postoperative TMD at the same position under the anterior occlusion. The contact stresses of the patients would decrease after BSSRO, but the degree of decrease varied individually which associated with the recovery of TMD. Regularly after orthognathic surgery, orthodontics should be operated to improve occlusion, and the stress distributions in the TMJs would be subsequently changed. However, the treatment, such as occlusal splint would be considered for the patients with abnormal contact stress under the anterior occlusion. Thus, finite element analysis would be helpful to design the postoperative orthodontics or occlusal splint and to predict the treatment effects.

The maximum and minimum principal stresses indicated the tensile and compressive characteristics. The maximum principal stresses of the disc, condyle, and temporal bone of the Postoperative group were significantly lower than those of the Preoperative group under the 2 occlusions (Fig. 3). However, there were no significant differences between the Postoperative group and the Control group. The results indicated that the osteotomy could improve the tensile characteristics of the disc, condyle, and temporal bone of the patients with facial asymmetry. The average peak maximum principal stresses of the disc in the Preoperative group at the non-deviated and deviated sides were >1.85 MPa under symmetric occlusions, which was the fracture stress determined by Kang et al[33] in their study. Long-term central and anterior occlusions for patients with facial asymmetry would probably lead to disc thinning or perforation. Intermediate zone of the disc in the asymptomatic subjects in this study always sustained the highest stresses because of its anatomic characteristics, in accordance with the study conducted by Beek et al.[34] However, the highest stress region of 4 non-deviated sides and 2 deviated sides of the 10 Preoperative patients were found to locate at the posterior bands. Experimental study[35] indicated that the anterior band and the intermediate zone were stronger in resisting tensile loads than the posterior band. That is to say, the patients with facial asymmetry would undertake the highest tensile stress at the weakest position-posterior band of disc, where disc perforation frequently occurred.[36] After the surgery, the counts of the highest tensile stress located in the posterior bands of disc were dropped to 1 at non-deviated side and 1 at deviated side, and for those located in the intermediate zones were 8 at non-deviated sides and 8 at deviated sides. After BSSRO, the distributions of tensile stress became normal. To avoid postoperative complications, finite element analyses should be performed to find out whether the postoperatively abnormal stress distributions exist. If the abnormal maximum principal stresses of discs are found, subsequent treatments such as occlusal splint have to be proceeded to improve the stress distributions of disc.

The preoperative minimum principal stresses at both sides of disc, condyle, and temporal bone were also significantly decreased after the surgery under the 2 occlusions (Fig. 4). Moreover, there was no significant difference existed between the Postoperative and Control groups. It indicated that the compressive characteristics of the disc, condyle, and temporal bone were also improved by BSSRO. Related research showed that the increased compression of condyles was a crucial factor in causing condylar resorption and mandibular relapse.[37] In this study, the minimum principal stress significantly decreased after BSSRO and was close to the asymptomatic subjects. No patients were found to have condylar resorption postoperatively, consistent with the previous observations. Therefore, the decrease of the compressive stresses of TMJ was considered as a beneficial aspect for BSSRO.

5. Conclusion

BSSRO could correct the asymmetry of stress distributions on both sides of TMJs for the patients with facial asymmetry. Moreover, BSSRO could decrease the magnitudes of the stresses in the TMJs and lead to stress distributions closer to the asymptomatic subjects. Subsequently, the improvements of stress distributions of TMJs for patients with facial asymmetry after BSSRO could release or remove the signs and symptoms of TMD.

Author contributions

Formal analysis: Jingheng Shu, Yuanli Zhang.
Methodology: Zhan Liu, Jie Yao.
Validation: Yuanli Zhang.
Writing – original draft: Jingheng Shu.
Writing – review and editing: Zhan Liu, Desmond Y.R. Chong.

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