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# Biomechanical study on the changes of stress in temporomandibular joints after the orthognathic surgery in patients with mandibular prognathism: a 3D finite element study

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*Purpose*: This study aimed to analyze the changes of the stress distributions in TMJs for the pre- and postoperative patients with mandibular prognathism under unilateral occlusions, a frequent occlusion in mastication. *Methods*: Pre- and six-mouth postoperative cone-beam computed tomography images of thirteen patients diagnosed with mandibular prognathism were scanned and used to construct complete maxillofacial models, assigned as the Pre and Post group, respectively. Another ten asymptomatic individuals were defined as the Control group. The inhomogeneous properties were assigned to the models. The muscle forces and boundary conditions corresponding to left and right unilateral occlusions were applied on the models. The analysis of variation (ANOVA) was chosen for the comparison among the groups. *Results*: The results showed that the Pre group had abnormal stress distributions ang higher stress level in TMJs, compared with those of the Post and Control groups. Moreover, from clinical cases, symptoms of temporomandibular disorders (TMDs) always followed with increased stresses. *Conclusion*: Generally, orthognathic surgeries could improve the stress distribution in TMJs of the patients with mandibular prognathism under the unilateral occlusions. However, the postoperative complications, especially symptoms of TMD, were closely related to changes of stress for patients with mandibular prognathism after orthognathic surgeries. Individual virtual surgery and finite element analysis should be conducted to prevent complications in TMJ.

*Key words*: *temporomandibular joint (TMJ), finite element method (FEM), mandibular prognathism, temporomandibular disorders (TMD)*

## 1. Introduction

The mandibular prognathism refers to the geometry of the mandible with lower dentition covering upper dentition, with a 25.5% prevalence in all kinds of mandibular deformities [27]. It can lead to chewing dysfunction, disorder occlusions and bad appearance, as well as psychological disturbances such as inferiority [2]. Moreover, symptoms of temporomandibular disorders (TMDs) also puzzle these patients, which is mainly caused by changes of internal degeneration of structures, such as disc displacement, condylar resorption, and disc perforation, etc. [26]. Bilateral sagittal split ramus osteotomy (BSSRO) is a surgery extensively used to correct mandibular prognathism with its good therapeutic effects on appearance and occlusion (Fig. 1). However, the consideration of structural changes of TMJ is limit. As a result, BSSRO brings some postoperative symptoms in TMJs; the most rele-

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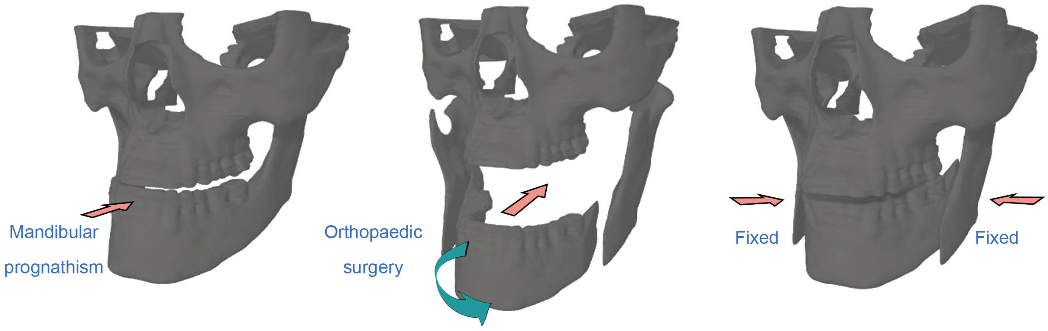


Fig. 1. Brief process of orthognathic surgeries for mandibular prognathism patients

vant symptoms is TMD [19], [26]. Previous studies reported that symptoms of TMDs have a great relationship with changes of the stresses in the TMJ [10], [24]. Thus, it is necessary to understand the relationships between mandibular prognathism, BSSRO, and stress distributions in TMJ.

BSSRO affects functions of TMJ in different ways. Some researchers pointed out that although BSSRO beautifies the appearance of patients, it still has possibility causing TMD symptoms [26]. And the positional and morphological changes of TMJ after surgeries may contribute to TMDs [1], [7]. Moreover, different surgical fixations also affect masticatory forces and TMJ loads after BSSRO through the animals' experiments, furtherly leading to TMDs [14], [15]. However, opposite opinions indicated that BSSRO restores occlusions for the patients, and alleviates or eliminates the symptoms of TMD [6], [21]. From biomechanical point of view, a proper biomechanical environment in TMJs has a good effect of recovery. Contrarily, various symptoms of TMD are associated with increased loads in TMJs [10]. Thus, the stress distributions in TMJs before and after BSSRO for the patients with mandibular prognathism should be investigated to find the relationship of postoperative TMD and loads.

Previous studies concentrated on morphological and positional changes of TMJs under the central occlusion [6], [25]. However, as unilateral occlusions are often seen in mastication, it is more meaningful to simulate the internal stress distribution under unilateral occlusions. This study firstly aims to evaluate differences of stress distribution in TMJs between pre- and postoperative mandibular prognathism patients, then to compare to those of the asymptomatic subjects under unilateral occlusions. Furthermore, stress distributions in TMJs for patients with pre- and postoperative symptoms of TMD are also analyzed.

# 2. Materials and methods

## 2.1. Establishment of the models

Thirteen mandibular prognathism patients (7 women and 6 men, 23.00 ± 2.98 years old) before and after BSSRO were recruited and assigned as the Pre and Post groups, respectively. Another 10 asymptomatic volunteers (4 women and 6 men, 26.70 ± 4.80 years old) without TMJ diseases assigned as the Control group. The inclusion criteria for patients in our study were: exceeding 18 years old; without prior TMJ procedures; diagnosis of mandibular prognathism with their upper dentitions covered by lower ones. The inclusion criteria for asymptomatic subjects were mentioned in previous study [18]. The research protocol was approved by the Institutional Review Board. All subjects were provided written informed consent.

All these subjects were scanned by cone-beam computed tomography (CBCT) with total 290 to 340 image slices and a 0.4-mm slice thickness (Fig. 2A). Then, the models of mandible, maxilla, and disc for each subject were established according to CBCT images in Mimics 15.0 (Materialise, Leuven, Belgium) (Fig. 2B-C) [21]. Then, the 3D models including mandible, maxilla, and discs were imported into a finite element analysis software ABAQUS 6.13 (Dassault, SIMULIA, RI).

## 2.2. Material properties

Based on a previous research [9], the interaction among discs, condyle and temporal bone was considered as contact with a frictional coefficient 0.001. Bone was considered as inhomogeneous according to empirical relations between gray values and elastic modulus [18] ((1)–(2)). The Poisson's ratios of articular discs and bone were 0.4 and 0.3, respectively [22]. Accord-

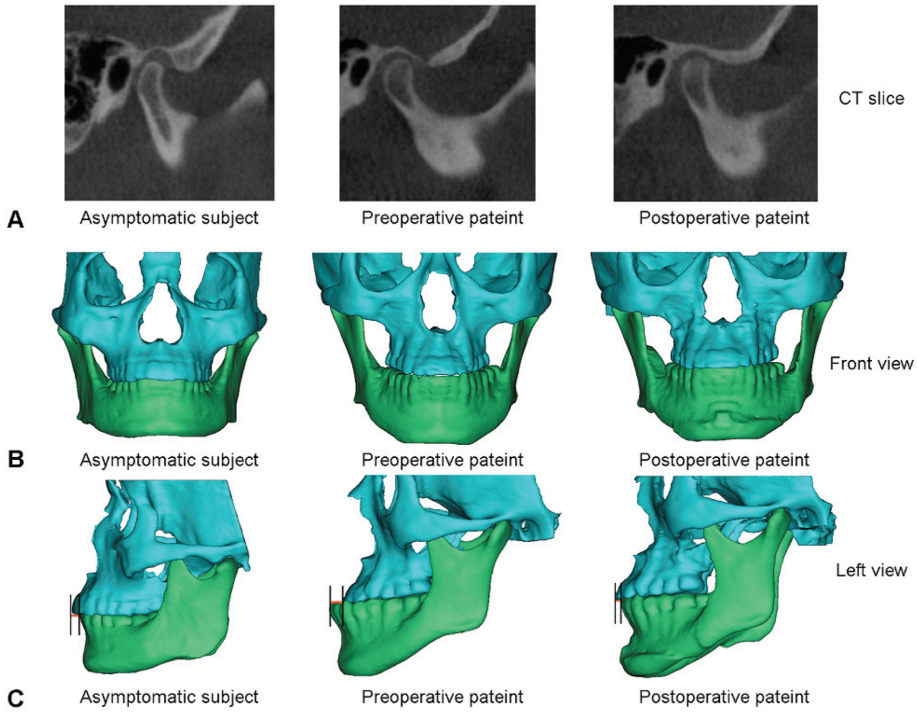


Fig. 2. A-C CT and 3D models of an asymptomatic subject and patient before and after the surgery:
A – CT slices of TMJ for an asymptomatic subject, a patient before and after BSSRO;
B – 3D models of an asymptomatic subject, a patient before and after BSSRO (Front view);
C – 3D models of an asymptomatic subject, a patient before and after BSSRO (Left view)

ing to the formulas, units were transferred to corresponding units in ABAQUS.

$$\text{Density} = -13.4 + 1017 \times \text{Gray value} \ldots \quad (1)$$

$$\text{Elastic modulus} = -388.8 + 5925 \times \text{Density} \ldots \quad (2)$$

## 2.3. Mesh

The models were meshed by the tetrahedron elements due to the complexity of the geometry. For the higher precision and contact algorithm, the mesh of TMJ regions was the 10-node quadratic element (C3D10M) (Fig. 3). The other regions were meshed by the 4-node linear elements (C3D4). The FE models were all consisted of over 150000 elements in total through previous convergence test [9].

## 2.4. Loading and boundary conditions

Muscle forces of unilateral occlusion were loaded on models [8], [16]. Apart from the central occlusion,

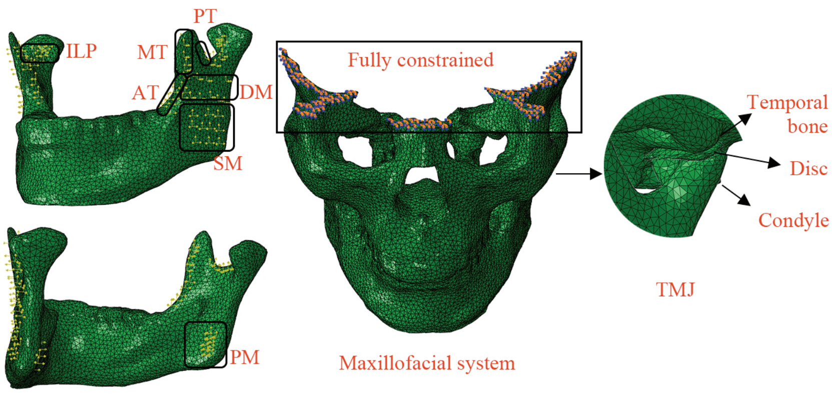


Fig. 3. The mesh, loadings and boundary conditions of the FE model with a detailed TMJ.
Notes: SM – superficial masseter; DM – deep masseter; MP – medial pterygoid;
AT – anterior temporalis; MT – middle temporalis; PT – posterior temporalis; ILP – inferior lateral pterygoid

muscles of each side during unilateral occlusion had different efficiencies. Furthermore, each muscle force in this study was applied on 10 nodes in the muscle area to properly simulate the attached area of the muscles. The top surface of maxilla was fully constrained. Left unilateral molar clenching (LMOL) and right unilateral molar clenching (RMOL), meaning that unilateral clenching primarily by left or right molars respectively, were applied on all subjects. The ipsilateral side to clenching side defined as the working side, and the contralateral side to clenching defined as the non-working side. Thus, the left and right sides were working and non-working sides under the LMOL, and non-working and working sides under the RMOL, respectively. The attachments were added between bone structures and discs according to the previous study [9]. Maximum and minimum principle stresses were chosen for representing the stress level of TMJ, and von Mises stresses were used for the illustration of stress distributions in TMJs.

## 2.5. Statistical analysis

Maximum and minimum principle stresses for three groups were included in statistical analysis, and the analysis of variance (ANOVA) and Student *t*-tests were performed in SPSS 20.0 (SPSS Inc, Chicago, IL). The statistically analysis about comparisons of stresses at working and non-working sides among three groups was analyzed by paired-samples *t*-test. Statistical differences among three groups were analyzed by ANOVA. Since structures and functions of asymptomatic subjects were healthy and stress distributions of the working and non-working sides under both occlusions were similar, only right unilateral occlusion (RMOL) was shown and compared in results of the Control group. The significance of the analysis was achieved as $P < 0.05$.

# 3. Results

## 3.1. Stress comparisons between two sides

Maximum and minimum principal stresses stresses for the Control group at the non-working side were significantly greater than those at the working side (Fig. 4). Postoperative maximum and minimum principle stresses at condyles exhibited significant differences between working and non-working sides, so as maximum principal stresses at temporal bones. However, no significant differences existed between both discs, condyles, and temporal bones in the Pre group.

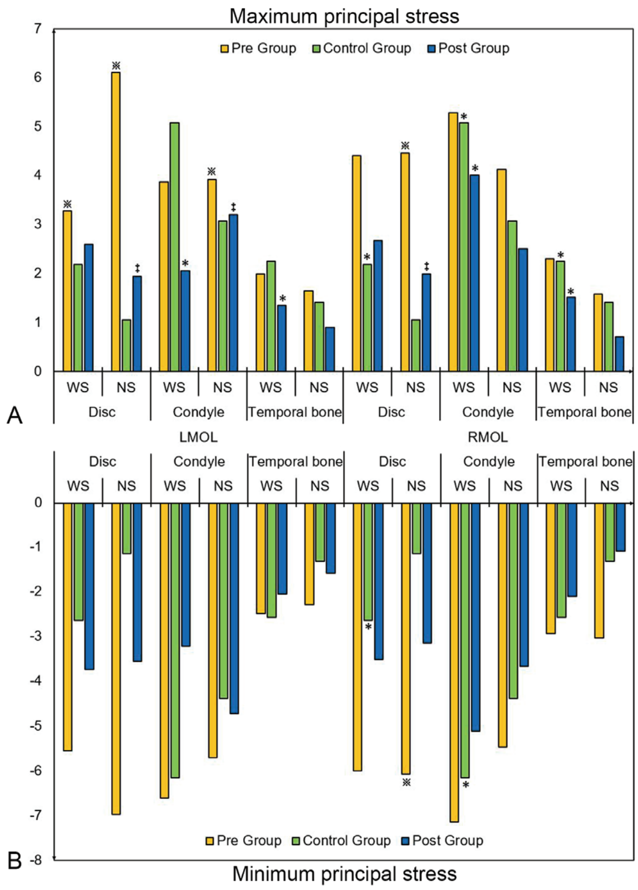


Fig. 4. A-B Comparisons of the peak stresses in the TMJs under the unilateral occlusions among the three groups (MPa) and stress comparisons of TMJs between working and non-working sides (MPa).
A – maximum principal stress; B: minimum principal stress;
※ exhibited significance between the Pre and Control group;
‡ exhibited significance between the Post and Control group;
* exhibited significance between two sides.
No significant difference existed between the Pre and Post group.
LMOL – left unilateral molar clenching;
RMOL – right unilateral molar clenching;
WS – working side; NS – non-working side

## 3.2. Changes of stress level

Maximum principal stresses of TMJs in the Pre group were greater than those of the Control group, except for those of condyles and temporal bones at working sides under the left unilateral occlusion (Fig. 3). Moreover, stresses of the Control group were greater than those of the Post group, especially in the condyle and temporal bone. Significances among the three groups were concentrated at the left unilateral occlusion.

The trend of minimum principal stresses was similar to that of maximum principal stresses. Stress levels of the Post group dropped down and were lower than those of the Control group, especially in condyles and temporal bones (Fig. 4). Stress levels of discs in the Post group were lower than those in the Pre and Control groups.

### 3.3. Changes of the stress distributions

High stress regions of asymptomatic individuals were located at the anterior of temporal bone at the non-working side, while the stresses at the working side was uniform without high stress region, so as the stress of disc. However, the stresses of the Pre group became irregular (Fig. 5) (only 1 patient as an example). Five patients concentrated on the lateral side of temporal bone and disc at non-working side, other three concentrated on the posterior part of disc at non-working side and another one concentrated on disc of the working sides. The remaining patients were close to normal. After the surgery, stress distributions for some patients were still abnormal and irregular, but the magnitudes was close to the Control group in this study.

## 4. Discussion

BSSRO provides an effective correction to remedy mandibular deformities. Although it has better performance on the improvement of appearance by changing bony structures, effects on TMJs are still divided. The remodeling of hard and soft tissues is also affected by orthognathic surgery [3], accompanied with changes of structures after the surgery. A previous study indicated that BSSRO provides a good improvement for facial asymmetric patients on stress distributions under the central and anterior occlusions, as well as recoveries of TMD symptoms [21]. There are also some opposite opinions for BSSRO, such as postoperative symptoms of TMD [20]. Furthermore, the unilateral occlusion is used with a higher frequency in daily mastication [23], providing a competitive influence on TMJ compared with central and anterior occlusions. Moreover, the stress analysis of mandibular prognathism patients under the unilateral occlusions is still lacking. Thus, the purpose of this study was to evaluate comparisons of the stress in TMJs under the unilateral occlusions between pre- and postoperative patients with mandibular prognathism.

The interaction of TMJs was considered as contact with a frictional coefficient 0.001 [11]. Five 3D maxillofacial models, whose material properties were

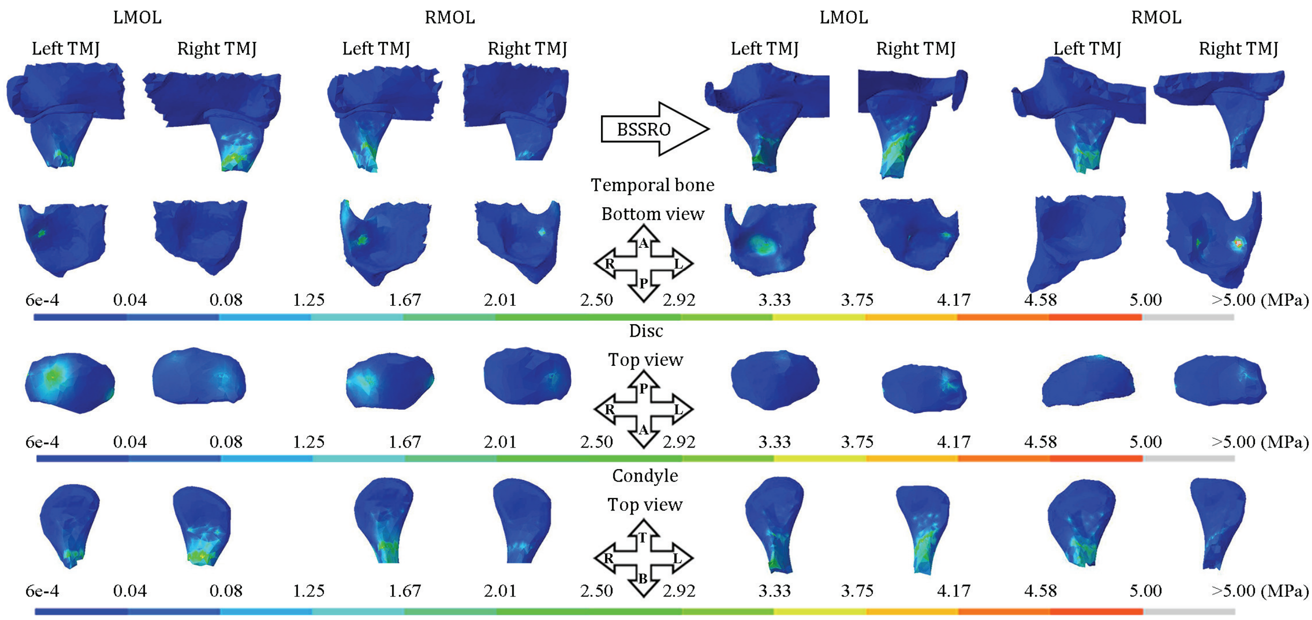


Fig. 5. The von Mises stress distributions of a mandibular prognathism patient before and after BSSRO. LMOL – left unilateral molar occlusion, RMOL – right unilateral molar occlusion, A – anterior, P – posterior, L – left, R – right, T – top, B – bottom

similar to maxillofacial system, were used to validate this method [28]. To the 3D models, vertical pressure on the top surface of the maxilla was added to simulate central occlusion. Finite element models and 3D models shared the same geometries, material properties, loads, and boundary conditions. The strain rosettes were attached on the mandible to record the vertical and horizontal strains. The results showed that the differences between experimental and simulated strains of the same monitoring point were within 5%. Thus, the interaction of TMJ simulated as contact with a 0.001 friction coefficient was reasonable. Moreover, the mandible and maxilla were considered as inhomogeneous materials, more realistic than homogeneous materials and rigid bodies.

## 4.1. The appearance of patients after BSSRO

The appearance of patients had a great improvement after surgeries. The position of condyles in mandibular prognathism patients was always nearer to the articular eminence, compared to the asymptomatic individuals (Fig. 2A), according to with da Silva et al.'s study [3]. The lower space would lead to the decrease of degree of freedom [29], [30], interfered with movements of the condyle in the glenoid fossa. In the case reports of this study, there was one patient that had serious preoperative limited opening of mouth. After surgeries, relative positions between upper and lower dentitions became normal with the recovery of limited opening of mouth (Fig. 2C). Thus, the proper interference in TMJs should be considered before the surgery to retain enough postoperative space between condyle and articular eminence, especially for patients with limited opening of mouth.

## 4.2. Effect of the mandibular prognathism and BSSRO on stress comparisons between both sides

The mandibular prognathism contributes to abnormal stress distributions in TMJs. Maximum and minimum principal stresses at the working side of the Control group were significantly lower than those at the non-working side. TMJs at working sides had more contact, while TMJs at non-working sides manifested greater stress level owing to larger movements at these sides under the unilateral occlusions. However, comparisons of stress between working and non-working sides of postoperative patients were not significantly different no matter whether under the left or right unilateral occlusions (Fig. 4). The stress levels of bilateral TMJs became close, different from the normal status in healthy individuals. The structures at the working side were as unstable and loose as those at the non-working side under unilateral occlusions, causing larger bilateral movements. After surgeries, although significances between the both sides reappeared and the trend was approaching to the normal individuals, it was still far from the status of normal individuals.

## 4.3. Effect of mandibular prognathism and BSSRO on stress level

Maximum and minimum principal stresses stand for tensile and compressive characteristics, respectively. In this study, maximum and minimum principal stresses of the disc, condyle, and temporal bone of the Post group were obviously lower than those of the Pre group under both unilateral occlusions (Fig. 4). Moreover, maximum and minimum principal stresses for the Post group of condyle and temporal bone under the right unilateral occlusion were lower than those of the Control group. It meant that the right unilateral occlusion was positive for the patients' recovery to avoid high stress. These differences between capabilities of left and right unilateral occlusions may result from the right chewing side preference. Diernberger et al.'s study exhibited larger percentage of population preferred to use right chewing [5]. Long-time chewing side preference caused functional decline of masticatory and occlusal force of non-working sides [12], corresponding to the masticatory capability of left sides in this study. However, disadvantages of long-time chewing side preference appeared as changes of aesthetics and caused of facial asymmetry [12]. Although the right unilateral molar clenching was better for decreasing the stress six months after surgeries, it was still risky for occurrence of facial or muscular asymmetry, even the asymmetry of body [13], [17]. Thus, suggestions should be arisen to avoid chewing side preference from the beginning of postoperative recoveries.

## 4.4. Effect of mandibular prognathism and surgeries on stress distributions

As an asymmetric loading, the unilateral molar clenching not only produced an asymmetric stress discrepancy between both sides, but also changed the stress distributions and high stress regions. In the asymptomatic subjects, the high stress regions of the discs at the non-working side were located at the anterior band, consistent with the other asymmetric loadings [4]. However, the nature of the stress in discs was correspondingly changed with the structural changes in the patients. The lateral part and the posterior band of the disc became other high stress regions, which may lead to the lateral disc displacement if long-term unilateral molar clenching remained. After the orthognathic surgery, although the magnitude of the stress dropped down, some patients were still in an abnormal stress distribution. From that point, postoperative orthodontics and occlusal reconstruction should be involved as the subsequent treatment.

## 4.5. Effect of mandibular prognathism and BSSRO on the symptoms of TMDs

From the biomechanical standpoint, the extra stress could cause TMD [10]. In other words, increased stresses of preoperative patients changed the normal biomechanical environment in TMJs, would be followed by

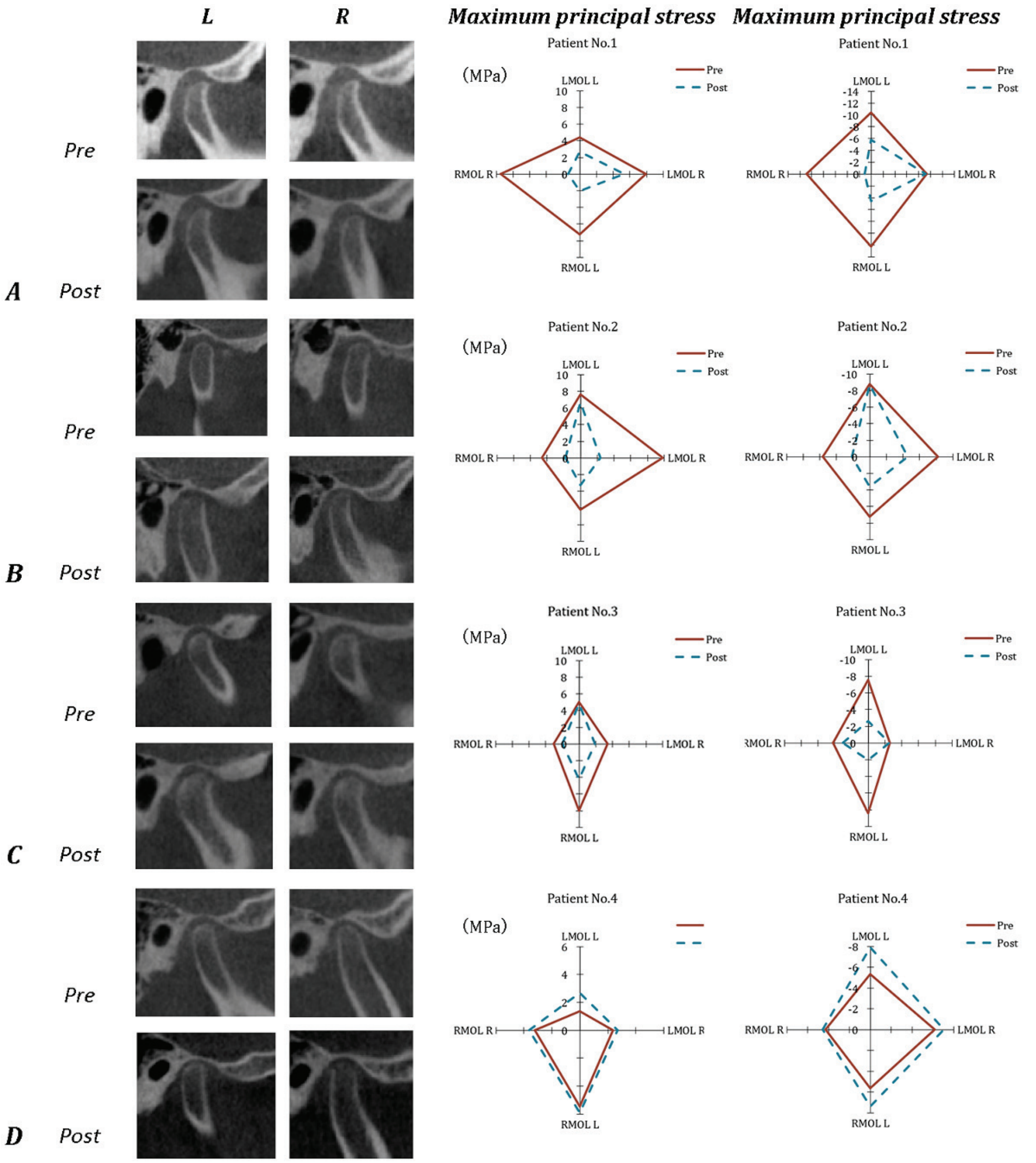


Fig. 6. The CT of TMJ and the comparisons of stress in disc between pre and postoperative patients associated with clicking joint. A – Patient No. 1 with preoperative clicking at right TMJ and without postoperative TMD, B – Patient No. 2 with preoperative clicking at left TMJ and with postoperative clicking only at beginning and ending of left TMJ during maximal opening. C – Patient No. 3 with preoperative clicking at both sides and without postoperative TMD. D – Patient No. 4 without preoperative TMD and with postoperative clicking at right TMJ

TMD. In our study, stresses of two of three patients with joint clicking were disappeared after surgeries (Fig. 6A and 6C), and symptoms of TMD in the remaining patient was alleviated (Fig. 6B). All the three patients were with the decreased stresses, always accompanied by the increased space between the anterior of condyle and articular eminence (Fig. 6). However, postoperative clicking of a patient without preoperative TMD appeared along with the increase of postoperative stresses (Fig. 6D). Thus, the occurrence of TMD in patients would originate from high stresses in the TMJ, consistently with previous study [10]. However, the stress level had individual differences. Although postoperative stresses of Patient No. 2 were still greater than those of postoperative Patient No. 4, postoperative symptoms of TMD were different (Fig. 6B and 6D). It was unavailable for us to obtain the stress magnitude that would lead to TMD. But it's clear that the increased stress postoperatively had more possibility to contribute to the symptoms of TMD.

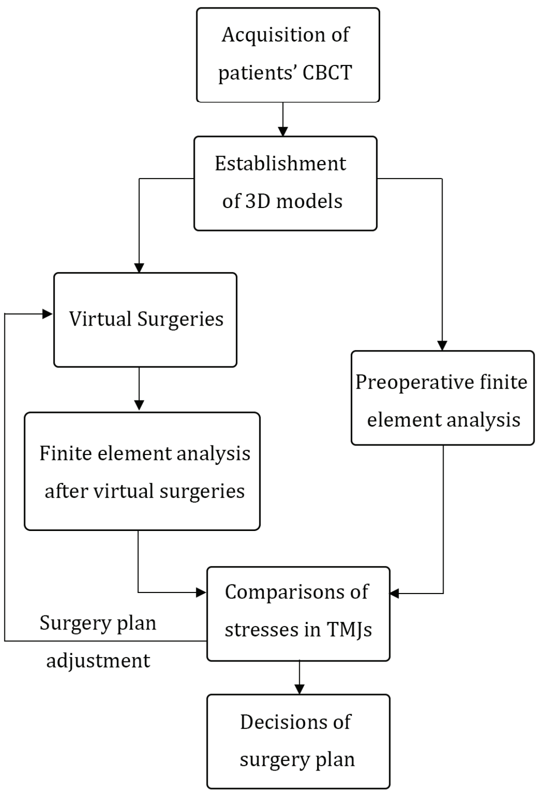


Fig. 7. Future workflow of treatment decisions for surgeons in combination with the biomechanical analysis

The comparison of pre- and postoperative stresses for patients was a feasible way according to virtual surgeries and FEA [20], beneficial for surgeons to adjust operative plans to decrease stresses in TMJs and avoid postoperative TMDs (Fig. 7). In the future, virtual surgeries and finite element analysis could be conducted to predict the possible postoperative internal biomechanical environment of TMJs, in order to provide more suitable treatment strategy for mandibular deformity patients. However, there are still some limitations in our study. One major limitation of this study was the muscle forces of individual cannot be detected due to the ethical consideration. Future detection technology may accurately access individual muscle forces, which can be used to verify findings such as ours.

# 5. Conclusion

In summary, effects of BSSRO on stresses in the TMJs of mandibular prognathism patients were generally positive. However, recoveries and occurrence of TMDs after surgeries differed individually. Increased stresses in the TMJs after the surgeries could lead to postoperative symptoms of TMD, while the decreased stress in the TMJs after the surgeries could contribute to recoveries of symptoms accompanied by the mandibular prognathism.

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## Ethics

All participants were prospectively provided with IRB (Institutional Review Board) and informed of consent from Stomatological Hospital of Chongqing Medical University.

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## Conflict of interest

The authors declare no conflict of interest related to this study.

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