

Computer Methods in Biomechanics and Biomedical Engineering

ISSN: 1025-5842 (Print) 1476-8259 (Online) Journal homepage: www.tandfonline.com/journals/gcmb20

Effects of condylar neck inclination and counterclockwise rotation on the stress distribution of the temporomandibular joint

Samira Alizada, Nurettin Diker & Dogan Dolanmaz

To cite this article: Samira Alizada, Nurettin Diker & Dogan Dolanmaz (2026) Effects of condylar neck inclination and counterclockwise rotation on the stress distribution of the temporomandibular joint, *Computer Methods in Biomechanics and Biomedical Engineering*, 29:4, 750-758, DOI: [10.1080/10255842.2024.2410229](https://doi.org/10.1080/10255842.2024.2410229)

To link to this article: <https://doi.org/10.1080/10255842.2024.2410229>



Published online: 07 Oct 2024.



Submit your article to this journal [↗](#)



Article views: 164



View related articles [↗](#)



View Crossmark data [↗](#)



Effects of condylar neck inclination and counterclockwise rotation on the stress distribution of the temporomandibular joint

Samira Alizada^a, Nurettin Diker^b  and Dogan Dolanmaz^c

^aDepartment of Oral and Maxillofacial Surgery, İstanbul, Turkey; ^bDepartment of Oral and Maxillofacial Surgery, Biruni University, İstanbul, Turkey; ^cDepartment of Oral and Maxillofacial Surgery, Bezmialem Vakif University, İstanbul, Turkey

ABSTRACT

Three different kinds of condylar inclination were manually modelled anteriorly inclined condylar neck, vertical condylar neck, and posteriorly inclined condylar neck. Three different maxillary impactions were simulated to evaluate the effect of counterclockwise rotation. The von Mises stresses of the disc, compressive stresses of the glenoid fossa, and compressive stresses of the condyle were the highest in the models with posteriorly inclined neck and lowest in the models with vertical condylar neck design. Stresses of the temporomandibular joint increase with the counterclockwise rotation of the maxilla-mandibular complex. The posteriorly inclined neck should be considered a risk factor for condylar resorption with increased counterclockwise rotation.

ARTICLE HISTORY

Received 30 November 2023
Accepted 24 September 2024

KEYWORDS

Orthognathic surgery;
Temporomandibular joint;
bone resorption;
mandibular osteotomy;
relapse

Introduction

Orthognathic surgical procedures are typical approaches for the treatment of maxillofacial deformities which cannot be corrected with conventional(non-surgical) orthodontic treatments. During mandibular orthognathic surgeries, the condyle can rotate and move to a new 3D location relative to the articular fossa while repositioning the proximal segment (Pergel et al. 2023). Previous researches indicated that condyles respond to these positional changes with remodelling and eventually in morphological changes to varying degrees in TMJs, surrounding soft tissues, and masticatory musculature (Jung et al. 2015). Besides condylar remodelling is a physiological response of TMJ to meet functional demands, with increased loading of TMJ with mandibular advancement may exceed the adaptive capacity of the TMJ and may give rise to condylar resorption (CR) (Mousoulea et al. 2017).

CR is defined as a progressive alteration in the condylar shape followed by a reduction in mass (Mousoulea et al. 2017). CR is a dreaded reason for late post-operative relapse and negatively affects the patient's overall satisfaction and consequence with an open bite tendency and reduction of mandibular projection (Catherine et al. 2016). Etiological factors can be divided into patient-related and surgery-related factors. Patient-related factors include female gender,

pre-operative TMJ dysfunction, mandibular hypoplasia with high mandibular occlusal plane angle, and posterior inclination of the condylar neck (Eggensperger et al. 2006; de Moraes et al. 2012). Surgery-related factors can be listed as the amount of mandibular advancement, type of fixation, and amount of counterclockwise rotation of the maxillomandibular complex (Eggensperger et al. 2006; de Moraes et al. 2012). The aim of the present study is to evaluate the effects of condyle neck inclination on the stress distribution of the temporomandibular joint in a patient with Class II skeletal deformity *via* finite element method (FEM). Furthermore, different amounts of maxillary impaction were simulated for each model to assess the effect of counterclockwise rotation on the stress distribution of the temporomandibular joint.

Material and methods

3D virtual model reconstruction

This study was approved by the human research ethics committee of Bezmialem Vakif University. The DICOM data of a 24-year-old female, who has no symptom of TMJ and full dentate was used for reconstruction of the three-dimensional model of the head. This patient has already been operated on for her Class II dentofacial deformity with mandibular advancement

and counterclockwise rotation. Axial computed tomography images have been taken for virtual surgical planning of the patient, were saved in DICOM format, and transferred to the NemoFAB software (Nemotech, Madrid, Spain) for reconstruction of the 3D virtual models of the patient, simulations of the osteotomies and simulations of the surgical movements. Routine virtual surgical planning sequences were followed. First, the head model constructed with DICOM data and dental model scans were merged into the head model. Then the records were oriented to the natural head position of the patient. After the segmentation of the maxilla and mandible, sagittal split ramus osteotomy with Hunsuck modification and Lefort I osteotomy was virtually made. Due to the surgical plan of the patient, 2 mm maxillary advancement was simulated first, and then three different impactions were simulated for investigation of the effect of counterclockwise rotation. First, 2 mm maxillary impaction was simulated, and then the mandibular segment was moved according to the planned final occlusion. The lower borders of the distal and proximal segments were aligned, thus proximal segment was rotated correspondingly to the rate of impaction (Figure 1). All independent models created and moved to a new position during virtual planning sequences were merged with Boolean operations and exported as a single STL file. Then the same procedure was followed for 4 mm and 6 mm impactions

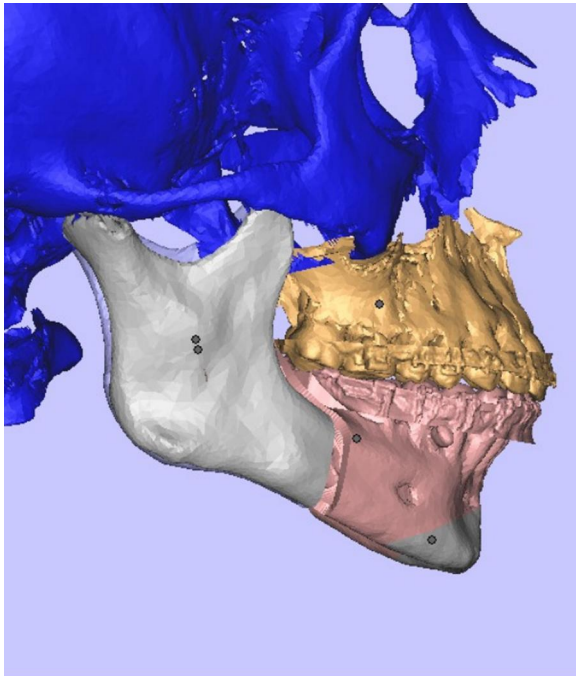


Figure 1. Relative positions of proximal segment, distal segment, maxillary segment and cranial base after simulation of maxillary impaction, counterclockwise rotation of distal and proximal mandibular segments.

respectively. All STL files were transferred to the ALTAIR Evolve Software (ALTAIR, Troy, MI, USA). Gaps between the osteotomy lines in the meshes were manually restored to simulate osseous healing in the osteotomy sites.

In the present study, three different kinds of condylar forms 1) anteriorly inclined condylar neck, 2) vertical condylar neck with no inclination, and 3) posteriorly inclined condylar neck were modelled. It was noticed that the current model of the patient has a posteriorly inclined condylar neck. By modifying the condylar morphology and ramus posterior border, the condylar neck with no inclination and anteriorly inclined condylar neck were manually modelled according to previous definitions made by authors (Hwang et al. 2000). These modifications were transferred to the models with different impactions thus, nine different kinds of bone models were obtained (Figure 2). Cortical and spongy bone were automatically assigned from the Hounsfield Units of CT into finite element models. Direct and tight contact was assumed at the boundary of the cortical and cancellous bone. A 3D model of a 1.0 mm profile miniplate was constructed based on a commercially available miniplate system (Level One 2.0, KLS Martin, Tuttlingen, Germany). Screw geometry was simplified into 2 mm diameter and 5 mm length cylinders. TMJ disc was also manually modelled and located according to the anatomical features and dimensions of the disc. ALTAIR Evolve software was used for all these manual constructions.

Meshing procedure

All models were imported to the ALTAIR Hypermesh software for the meshing procedure. The models were meshed with 3D quadratic tetrahedral elements. In the area of the TMJs, the mesh was refined by increasing the number of nodes to obtain more accurate results. As a result, the smallest model has 444937 nodes and 1738968 elements, while the largest model has 463558 nodes and 1818510 elements.

Boundary conditions and loading

In the present study, a homogenous, linearly elastic, and isotropic material description was used to define the material properties of cortical bone, spongy bone, TMJ disc, and titanium alloy. Young's modulus and Poisson's ratios for simulated materials are presented in Table 1. The unilateral 100 N load was applied to the left, first mandibular molar perpendicular

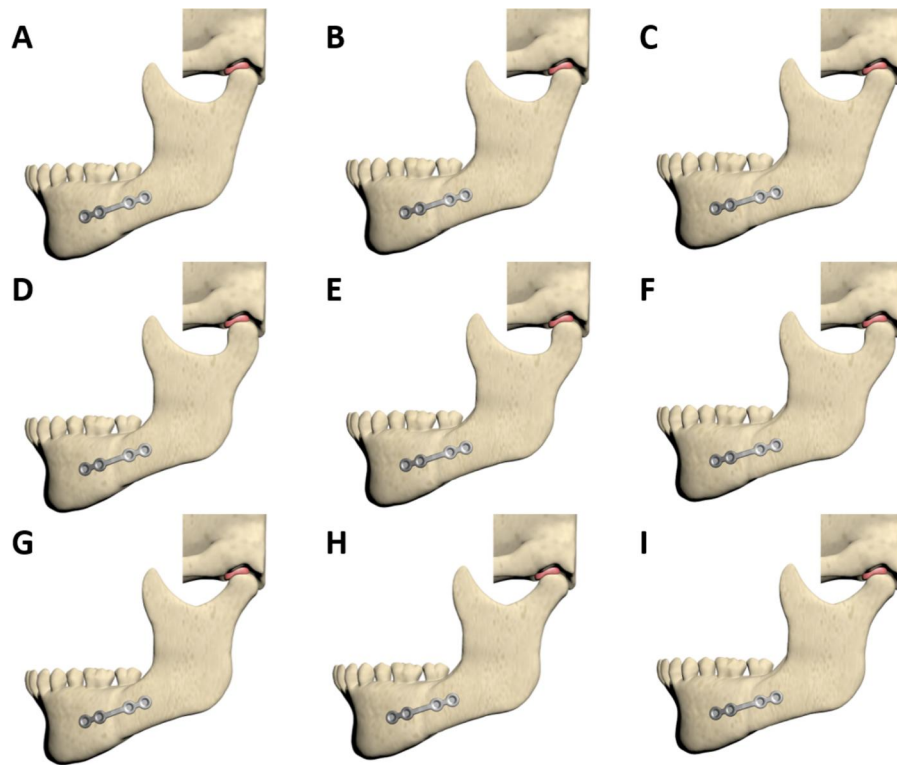


Figure 2. Models with different impactation simulations and condylar neck morphologies. A) 2 mm maxillary impactation simulated model with vertical condylar neck. B) 4 mm maxillary impactation simulated model with vertical condylar neck. C) 6 mm maxillary impactation simulated model with vertical condylar neck. D) 2 mm maxillary impactation simulated model with anteriorly inclined condylar neck. E) 4 mm maxillary impactation simulated model with anteriorly inclined condylar neck. F) 6 mm maxillary impactation simulated model with anteriorly inclined condylar neck. G) 2 mm maxillary impactation simulated model with posteriorly inclined condylar neck. H) 4 mm maxillary impactation simulated model with posteriorly inclined condylar neck. I) 6 mm maxillary impactation simulated model with posteriorly inclined condylar neck.

Table 1. Material properties.

	Elastic Modulus	Poisson Ratio
Cortical bone (Nurettin and Burak 2018)	13.700	0.3
Cancellous bone (Nurettin and Burak 2018)	1.500	0.3
TMJ disc (Silva et al. 2020)	44.1	0.4
Titanium Alloy (Nurettin and Burak 2018)	110.000	0.34

to the occlusion plane. Regarding boundary conditions, the bilateral nodes of the superior border of the temporal bones and the inferior border of the symphysis were constrained in all directions. The interfaces between the TMJ disc-condyle, as well as the TMJ disc-glenoid fossa, were regarded as surface-to-surface contacts with a frictional coefficient of 0.001. All the other interfaces between the models (miniplate-screw contacts and screw-bone contacts) were considered bonded contacts. Totally 9 nonlinear analyses were made for 9 models. von Mises stress values of the TMJ disc and principal compressive stress (minimum principal stress) of the condyle and the glenoid fossa in the temporal bone were evaluated.

Results

von Mises stress values of the TMJ disc and minimum principal stress of the condyle and the glenoid fossa were 5-20% higher on the left (functioning) side. So, stresses on the functioning side were considered for comparison between the groups in the present study.

Von Mises stresses of the TMJ disc

Maximum von Mises stresses were evaluated in the both upper and lower surfaces of the TMJ disc. The maximum von Mises stresses were observed in the most concave point on the superior surface of the TMJ disc facing to glenoid fossa in all models (Figure 3). The highest von Mises stress of the TMJ disc was noted in the model with 6 mm impactation and posteriorly inclined neck design, on the other hand, the lowest von Mises stress was noted in the model with 2 mm impactation and no inclined neck design. It was noted that stresses of the TMJ disc

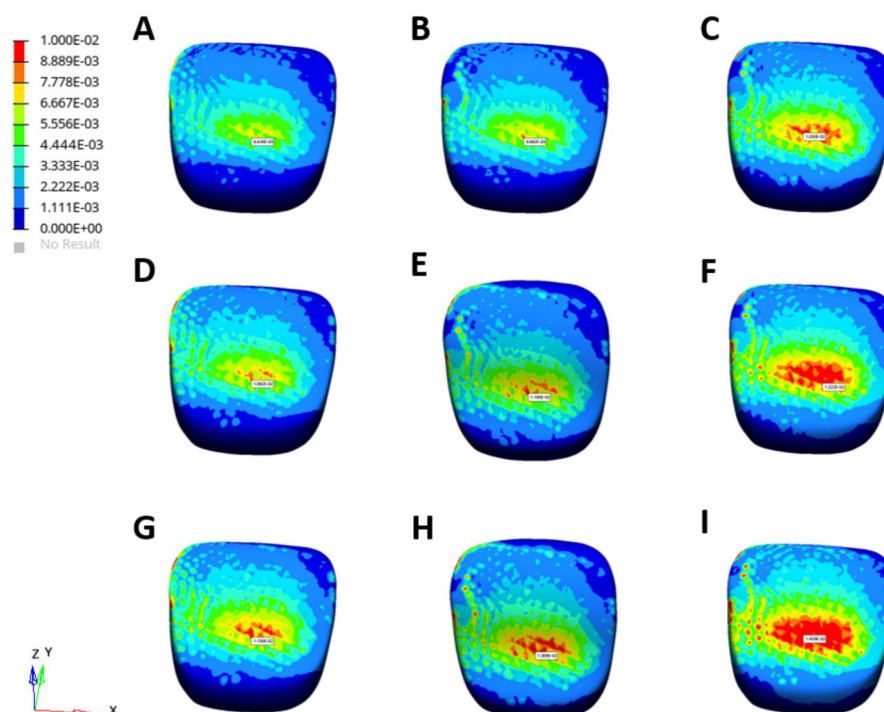


Figure 3. Von Mises stresses of the TMJ disk. A) 2 mm maxillary impaction simulated model with vertical condylar neck. B) 4 mm maxillary impaction simulated model with vertical condylar neck. C) 6 mm maxillary impaction simulated model with vertical condylar neck. D) 2 mm maxillary impaction simulated model with anteriorly inclined condylar neck. E) 4 mm maxillary impaction simulated model with anteriorly inclined condylar neck. F) 6 mm maxillary impaction simulated model with anteriorly inclined condylar neck. G) 2 mm maxillary impaction simulated model with posteriorly inclined condylar neck. H) 4 mm maxillary impaction simulated model with posteriorly inclined condylar neck. I) 6 mm maxillary impaction simulated model with posteriorly inclined condylar neck. (X: mediolateral direction, Y: anteroposterior direction, Z: inferosuperior direction).

progressively increase with the amount of maxillary impaction for all kinds of condylar morphology. Moreover, independently of the amount of maxillary impaction, stresses of the TMJ disc were the highest in the models with posteriorly inclined neck design and lowest in the models with no inclined neck design. (Table 2).

Minimum principal (compressive) stresses of the condyle

The maximum compressive stresses in the condyle were observed at the superior-anterior surface of the condylar head facing the most convex point on the lower surface of the TMJ disk in all models (Figure 4). The highest Minimum Principal stress of the condyle was noted in the model with 6 mm impaction and posteriorly inclined neck design on the contrary, the lowest minimum principal stress was noted in the model with 2 mm impaction and no inclined neck design. It was noted that stresses in condyle progressively increase with the amount of maxillary impaction for all kinds of condylar morphology. Furthermore, stresses of the condyle were the highest in the models

Table 2. Comparison of peak von Mises stresses of the TMJ disc (kPa).

	2 mm	4 mm	6 mm
Condyle with no inclination	8.4	9.7	10.5
Anteriorly inclined condyle	10	12	12.2
Posteriorly inclined condyle	11	13.6	14

with posteriorly inclined neck design and lowest in the models with no inclined neck design for all evaluated amounts of maxillary impaction (Table 3).

Minimum principle (compressive) stresses of the glenoid fossa

The maximum compressive stresses in the glenoid fossa were observed at the anterior slop of the glenoid fossa facing to the most concave point on the upper surface of the TMJ disk in all models (Figure 5). The highest Minimum Principal stresses of the glenoid fossa was noted in the model with 6 mm impaction and posteriorly inclined neck design however, the lowest minimum principal stress was noted in the model with 2 mm impaction and no inclined neck design. It was noted that stresses in condyle progressively increase with the amount of maxillary

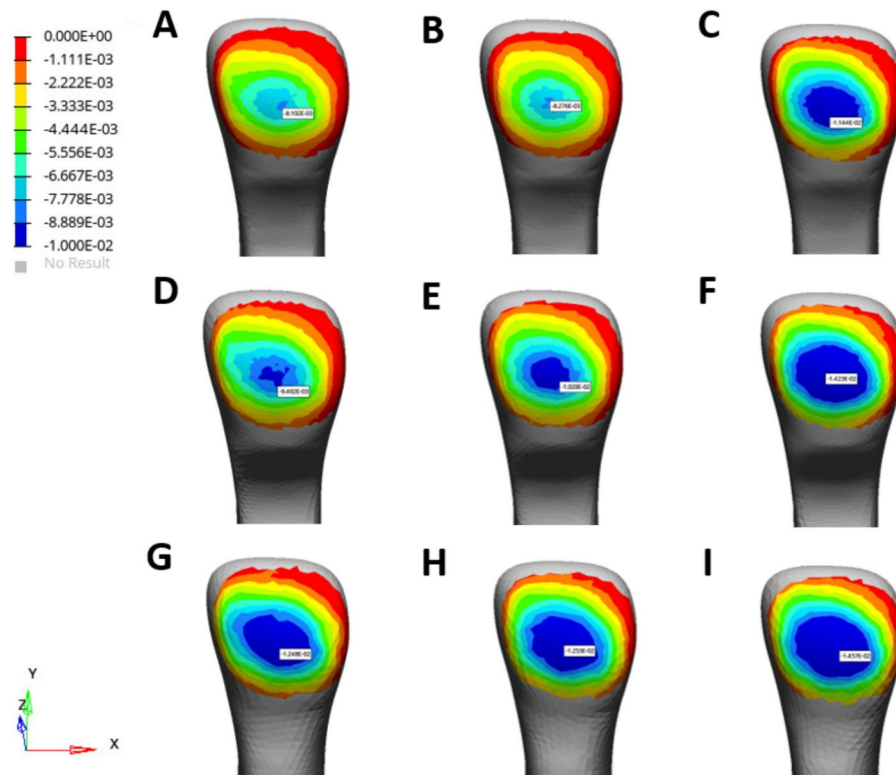


Figure 4. Minimum principal (compressive) stresses of the condyle. A) 2 mm maxillary impactation simulated model with vertical condylar neck. B) 4 mm maxillary impactation simulated model with vertical condylar neck. C) 6 mm maxillary impactation simulated model with vertical condylar neck. D) 2 mm maxillary impactation simulated model with anteriorly inclined condylar neck. E) 4 mm maxillary impactation simulated model with anteriorly inclined condylar neck. F) 6 mm maxillary impactation simulated model with anteriorly inclined condylar neck. G) 2 mm maxillary impactation simulated model with posteriorly inclined condylar neck. H) 4 mm maxillary impactation simulated model with posteriorly inclined condylar neck. I) 6 mm maxillary impactation simulated model with posteriorly inclined condylar neck. (X: mediolateral direction, Y: anteroposterior direction, Z: inferosuperior direction).

Table 3. Comparison of peak compressive stresses of the condyle (kPa).

	2 mm	4 mm	6 mm
Condyle with no inclination	8.1	8.27	11.4
Anteriorly inclined condyle	9.4	10.2	14.2
Posteriorly inclined condyle	12.4	12.5	14.5

impaction for all kinds of condylar morphology. Furthermore, stresses of the condyle were the highest in the models with posteriorly inclined neck design and lowest in the models with no inclined neck design for all evaluated amounts of maxillary impactation (Table 4).

Discussion

Factors such as improving mastication, swallowing, and speech functions besides facial aesthetics are motivating factors for patients undergoing orthognathic surgery. During orthognathic surgeries, the position of the condyles with the glenoid fossa can be altered during the repositioning of the condylar segments. Condyle, disk, soft tissues around the TMJ,

and musculature adapt to these positional changes. When these changes exceed the adaptive limits of the condyle CR may occur (Jung et al. 2015). Moreover, excessive changes in TMJ load have been considered as the cause of degeneration changes (Li et al. 2020). Therefore, surgeons should stay within the adaptive limits of the TMJ structures during the planning of the orthognathic surgery cases. Consequently, it is important to know the effects of patient-related factors and surgery-related factors on TMJ structures after orthognathic surgery as much as possible. In the present study, we evaluated the post-operative long-term effects of condyle neck morphology and the amount of counterclockwise rotation of the mandible on TMJ structures in a patient with Class II skeletal deformity.

FEM is a numerical method for solving mechanical problems for complex structures. Due to its great reproducibility and reliability, there is many researches with this technique in different parts of dentistry (Aktas and Diker 2023; Mori et al. 2010). In addition, there is not any experimental and ethical technique to evaluate the load of a joint in the body. Therefore, it

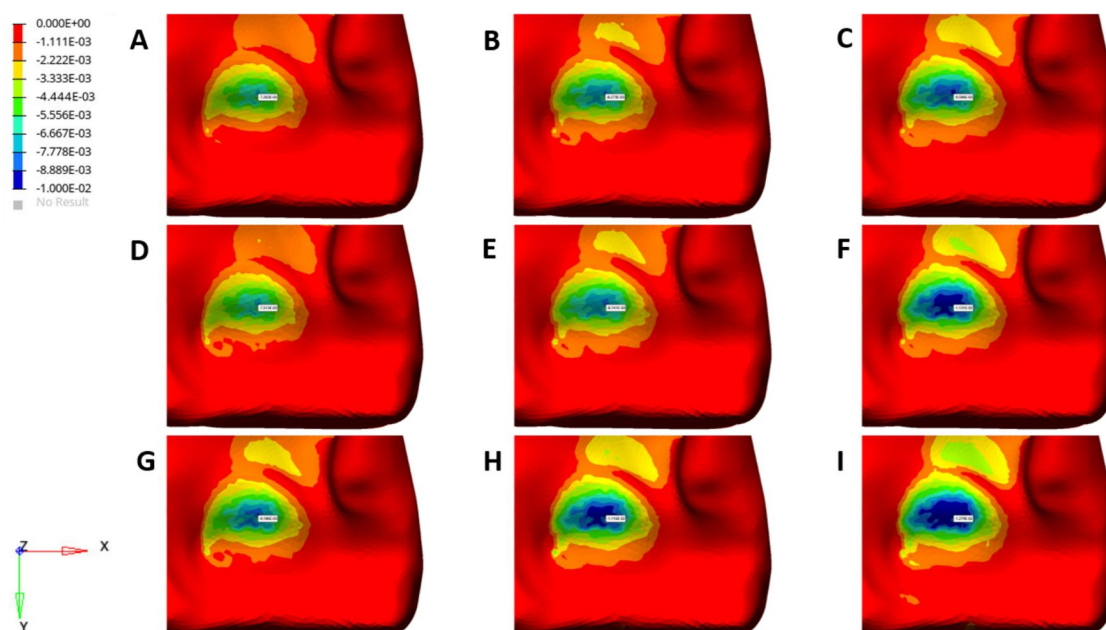


Figure 5. Minimum principal (compressive) stresses of the glenoid fossa. A) 2 mm maxillary impactation simulated model with vertical condylar neck. B) 4 mm maxillary impactation simulated model with vertical condylar neck. C) 6 mm maxillary impactation simulated model with vertical condylar neck. D) 2 mm maxillary impactation simulated model with anteriorly inclined condylar neck. E) 4 mm maxillary impactation simulated model with anteriorly inclined condylar neck. F) 6 mm maxillary impactation simulated model with anteriorly inclined condylar neck. G) 2 mm maxillary impactation simulated model with posteriorly inclined condylar neck. H) 4 mm maxillary impactation simulated model with posteriorly inclined condylar neck. I) 6 mm maxillary impactation simulated model with posteriorly inclined condylar neck. (X: mediolateral direction, Y: anteroposterior direction, Z: inferosuperior direction).

Table 4. Comparison of peak compressive stresses of the glenoid fossa (kPa).

	2 mm	4 mm	6 mm
Condyle with no inclination	7.26	8.27	9.60
Anteriorly inclined condyle	7.51	8.74	11.3
Posteriorly inclined condyle	9.18	11.1	12.8

is obligatory to create an FEA model of the TMJ for the evaluation of joint load (Commisso et al. 2014). The stresses in the jaws and related structures increase with the increasing biting forces. Patients usually avoid chewing and biting foods for several weeks to several months after the orthognathic surgery and a comprehensive meta-analysis by Bunpu et al. showed that, bite forces of the orthognathic surgery patients at the 6 months post-surgery period were less than %50 of bite forces of non-operated people (Bunpu and Changsiripun 2023). Thus, consequences of load on CR happen in the long term post-operative period. When patients start to make notable forces the bony healing in the osteotomy sides has already happened. Accordingly, 100 N biting force in the molar region was chosen as a biting force in the current study which is significantly lower than the biting force of a non-operated person and gaps between osteotomy lines were restored to simulate bony healing. The properties of the materials are considered during the

evaluation of stress analysis. Principle stresses are considered for brittle materials such as bone, porcelain, and hard tissues of the tooth, whereas Von Mises stress is considered for the analysis of ductile materials such as metals (Küçük Kurt 2017). Thus, Von Mises stresses were considered for the TMJ disc and minimum principal stresses (compressive stresses) were considered for both condyle and glenoid fossa in the present study. As can be interpreted from the results of the study, the highest stresses occur on the surfaces of the condyle, disc and fossa facing each other. Failures of the anatomical structures occur when stress on them exceeds the yield strength of the material or as a fatigue failure after cyclic loading. The fatigue life of structures is influenced by the maximum stress of the structures under specific loads and the number of loading cycles. Theoretically, fatigue life can be increased by decreasing the highest stress in the structure. Significantly lower stresses with little clinical significance were observed in the anterior, posterior, lateral and medial sides of the components where the highest stresses were observed.

During FEA the stress observed in soft tissues, such as the articular disk in the present study is lower compared to the stress observed in load-bearing hard tissues such as the corpus or symphysis of the mandible (Nurettin and Burak 2018). However, the

likelihood of fatigue failure in living tissue depends on the magnitude and frequency of the observed stress (Nickel et al. 2009). The compressive strain produced during a static period of loading, frequency, and magnitude of applied mechanical work imposed on a volume of the TMJ disk can be listed as variables determining the mechanical fatigue rate of articulating surfaces (Murakami et al. 2023). Furthermore, Gallo et al. reported that high energy density is possibly a unique mechanism of cartilage fatigue in individuals with TMJ pain and disk displacement (Gallo L R Iwasaki et al. 2015).

Hwang et al. defined three different kinds of condylar form regarding the angle between the vertical axis of the ramus and the line drawn through the top of the condylar head and the centre of the broadest part of the condyle. These three condylar forms were modelled and investigated in the present study as anteriorly inclined condylar neck, vertical condylar neck, and posteriorly inclined condylar neck (Hwang et al. 2000). Furthermore, they made the cephalometric evaluation of 240 Angle Class II patients 2 years after orthognathic surgery and identified CR in 11 patients. These cases were retrospectively evaluated for possible anatomical and surgical risk factors for CR. It has been shown that all patients with CR had posteriorly inclined condylar necks. In another study by Hwang et al. they compared 17 patients with postoperative CR with 22 patients without postoperative CR and found that posterior inclination of the condylar neck should be considered a nonsurgical risk factor for CR (Hwang et al. 2004). A similar classification was made by Hoppenreijns et al. who stated that condyles with a height-to-width ratio of less than 1 and condyles with posteriorly inclined neck seems to be more at risk for CR (Hoppenreijns et al. 1999). The results of the present study showed that models with posteriorly inclined condylar necks have the highest stresses in all evaluated anatomical structures. Von Mises stresses of TMJ disk were %30-40 higher in the models with posteriorly inclined neck compared with the models with no inclination, minimum principal stresses of condyle were %27-53 higher in the models with posteriorly inclined neck compared with the models with no inclination and minimum principal stresses of glenoid fossa were %26-35 higher in the models with posteriorly inclined neck compared with the models with no inclination. All results of the present study are comparable with the findings of the previous studies mentioned above.

A step at the buccal osteotomy site is formed between the proximal and distal segments during

BSSO, especially in the case of anterior and superior mandibular movement. Surgeons usually prefer to reposition the inferior border of the proximal segment to avoid postoperative antegonial notch, thus counterclockwise rotation also happens in the condylar segment. This rotational change is considered as a risk factor for CR by several researchers, particularly in cases with large mandibular advancement (Togninalli et al. 2022; Vandeput et al. 2019; Teltzrow et al. 2005). The rationale behind this theory is that counterclockwise rotation of the condylar segment brings less dense and formerly unloaded anterior surface of the condyle more superiorly (Mousoulea et al. 2017; O’Ryan and Epker 1984; Kobayashi et al. 2012). This theory also explains the susceptibility of the posteriorly inclined condylar neck for CR. In the case of a posteriorly inclined condylar neck, the less loaded anterior-superior area of the condyle is more exposed to loading (Mousoulea et al. 2017). In a comprehensive review of Togninalli et al. anterior rotation of the mandible during surgery in young women is considered as a risk factor of CR (Togninalli et al. 2022). The effect of rotational movement of the proximal segment was also evaluated in the previously mentioned study of Hwang et al. and it has been showed that all patients with condylar resorption had a counterclockwise rotation of the proximal segment, that is 6.78° ($2.5\text{--}12.0^\circ$) on average (Hwang et al. 2000). Moreover, in the retrospective study of Hwang et al. preoperative cephalometric parameters related to hyperdivergent facial vertical pattern, which usually necessitate counterclockwise rotation of the mandible, were considered a relevant risk factor for CR in bimaxillary orthognathic surgery patients (Hwang et al. 2004). The results of the present study showed that stresses in all evaluated anatomical structures increase with increasing rotation of the mandible. Von Mises stresses of TMJ disk were %22-27 higher in the models with 6 mm maxillary impaction compared with the models with 2 mm maxillary impaction, minimum principal stresses of condyle were %17-51 higher in the models with 6 mm maxillary impaction compared with the models with 2 mm maxillary impaction and minimum principal stresses of glenoid fossa were %32-50 higher in the models with 6 mm maxillary impaction compared with the models with 2 mm maxillary impaction. All results of the present study are consistent with what has been found in previous studies mentioned above.

There are certain limitations of FEM as it is a computerized *in vitro* study in which clinical conditions may not be completely simulated. Stress analysis is

usually conducted under static loading, and the mechanical properties of materials are set as isotropic and linearly elastic, although it is not so in reality. However, within the limitations of the present study, it can be concluded that stresses in the condylar head, glenoid fossa, and TMJ disc increase with the increasing impaction of the maxilla and counterclockwise rotation of the proximal segments. Condyles with no inclination present the most favourable morphological subtype according to TMJ loads. Stresses of the TMJ increase in the case of anteriorly inclined condylar neck and posteriorly inclined condylar neck morphology leading to the highest stresses of the TMJ. The surgeon should consider morphological features of the condyle and other reported non-surgical factors found to be related to CR in the literature during surgical planning. Consequently, surgeons may consider adding genioplasty to the surgical plan for controlling vertical dimension, instead of increasing the counterclockwise rotation to decrease the risk of CR.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The present study was supported by Scientific Research Projects Coordination Unit of Bezmialem Vakif University (Project No: 20221009).

ORCID

Nurettin Diker  <http://orcid.org/0000-0002-7825-1083>

References

- Aktas T, Diker N. 2023. Biomechanical effects of inclined implant shoulder design in all-on-four treatment concept: a three-dimensional finite element analysis. *Biomed Eng/ Biomed Tech.* 68(6):583–591. doi: [10.1515/bmt-2023-0002](https://doi.org/10.1515/bmt-2023-0002).
- Bunpu P, Changsiripun C. 2023. Assessment of masticatory performance in patients undergoing orthognathic surgery: a systematic review and meta-analysis. *J Oral Rehabil.* 50(7):596–616. doi: [10.1111/joor.13447](https://doi.org/10.1111/joor.13447).
- Catherine Z, Breton P, Bouletreau P. 2016. Management of dentoskeletal deformity due to condylar resorption: literature review. *Oral Surg Oral Med Oral Pathol Oral Radiol.* 121(2):126–132. doi: [10.1016/j.oooo.2015.08.013](https://doi.org/10.1016/j.oooo.2015.08.013).
- Commisso MS, Martínez-Reina J, Mayo J. 2014. A study of the temporomandibular joint during bruxism. *Int J Oral Sci.* 6(2):116–123. doi: [10.1038/ijos.2014.4](https://doi.org/10.1038/ijos.2014.4).
- de Moraes PH, Rizzati-Barbosa CM, Olate S, Fernandes Moreira RW, de Moraes M. 2012. Condylar resorption after orthognathic surgery: a systematic review. *Int J Morphol.* 30(3):1023–1028. doi: [10.4067/S0717-95022012000300042](https://doi.org/10.4067/S0717-95022012000300042).
- Eggensperger N, Smolka K, Luder J, Iizuka T. 2006. Short- and long-term skeletal relapse after mandibular advancement surgery. *Int J Oral Maxillofac Surg.* 35(1):36–42. doi: [10.1016/j.ijom.2005.04.008](https://doi.org/10.1016/j.ijom.2005.04.008).
- Gallo L R Iwasaki YM, Gonzalez H, Liu DB, Marx JC, Nickel LM, Iwasaki LR, Liu H, Nickel JC, Gonzalez YM, Marx DB, et al. 2015. Diagnostic group differences in temporomandibular joint energy densities. *Orthod Craniofac Res.* 18 Suppl 1(0 1):164–169. doi: [10.1111/OCR.12074](https://doi.org/10.1111/OCR.12074).
- Hoppenreijts TJM, Stoelinga PJW, Grace KL, Robben CMG. 1999. Long-term evaluation of patients with progressive condylar resorption following orthognathic surgery. *Int J Oral Maxillofac Surg.* 28(6):411–418. doi: [10.1016/s0901-5027\(99\)80052-6](https://doi.org/10.1016/s0901-5027(99)80052-6).
- Hwang SJ, Haers PE, Sailer HF. 2000. The role of a posteriorly inclined condylar neck in condylar resorption after orthognathic surgery. *J Craniomaxillofac Surg.* 28(2):85–90. doi: [10.1054/jcms.2000.0129](https://doi.org/10.1054/jcms.2000.0129).
- Hwang SJ, Haers PE, Seifert B, Sailer HF. 2004. Non-surgical risk factors for condylar resorption after orthognathic surgery. *J Craniomaxillofac Surg.* 32(2):103–111. doi: [10.1016/j.jcms.2003.09.007](https://doi.org/10.1016/j.jcms.2003.09.007).
- Jung HD, Kim SY, Park HS, Jung YS. 2015. Orthognathic surgery and temporomandibular joint symptoms. *Maxillofac Plast Reconstr Surg.* 37(1):14. doi: [10.1186/s40902-015-0014-4](https://doi.org/10.1186/s40902-015-0014-4).
- Kobayashi T, Izumi N, Kojima T, Sakagami N, Saito I, Saito C. 2012. Progressive condylar resorption after mandibular advancement. *Br J Oral Maxillofac Surg.* 50(2):176–180. doi: [10.1016/j.bjoms.2011.02.006](https://doi.org/10.1016/j.bjoms.2011.02.006).
- Küçük Kurt S. 2017. Sonlu elemanlar stres analiz yöntemi ve dental implantoloji alanında yapılan araştırmalar. *Atatürk Üni Diş Hek FakDerg.* 29(4):701–710.
- Li H, Zhou N, Huang X, Zhang T, He S, Guo P. 2020. Biomechanical effect of asymmetric mandibular prognathism treated with BSSRO and USSRO on temporomandibular joints: a three-dimensional finite element analysis. *Br J Oral Maxillofac Surg.* 58(9):1103–1109. doi: [10.1016/j.bjoms.2020.06.006](https://doi.org/10.1016/j.bjoms.2020.06.006).
- Mori H, Horiuchi S, Nishimura S, Nikawa H, Murayama T, Ueda K, Ogawa D, Kuroda S, Kawano F, Naito H, et al. 2010. Three-dimensional finite element analysis of cartilaginous tissues in human temporomandibular joint during prolonged clenching. *Arch Oral Biol.* 55(11):879–886. doi: [10.1016/j.archoralbio.2010.07.011](https://doi.org/10.1016/j.archoralbio.2010.07.011).
- Mousoulea S, Kloukos D, Sampaziotis D, Vogiatzi T, Eliades T. 2017. Condylar resorption in orthognathic patients after mandibular bilateral sagittal split osteotomy: a systematic review. *Eur J Orthod.* 39(3):294–309. doi: [10.1093/ejo/cjw045](https://doi.org/10.1093/ejo/cjw045).
- Murakami K, Yamamoto K, Kawakami M, Horita S, Kirita T. 2023. Changes in strain energy density in the temporomandibular joint disk after sagittal split ramus osteotomy using a computed tomography-based finite element model. *J Orofac Orthop.* 85(4):289–305. doi: [10.1007/S00056-022-00441-3/TABLES/2](https://doi.org/10.1007/S00056-022-00441-3/TABLES/2).
- Nickel J, Spilker R, Iwasaki L, Gonzalez Y, McCall WD, Ohrbach R, Beatty MW, Marx D. 2009. Static and dynamic

- mechanics of the temporomandibular joint: plowing forces, joint load and tissue stress. *Orthod Craniofac Res.* 12(3): 159–167. doi: [10.1111/J.1601-6343.2009.01449.X](https://doi.org/10.1111/J.1601-6343.2009.01449.X).
- Nurettin D, Burak B. 2018. Feasibility of carbon-fiber-reinforced polymer fixation plates for treatment of atrophic mandibular fracture: a finite element method. *J Craniomaxillofac Surg.* 46(12):2182–2189. doi: [10.1016/j.jcms.2018.09.030](https://doi.org/10.1016/j.jcms.2018.09.030).
- O’Ryan F, Epker BN. 1984. Temporomandibular joint function and morphology: observations on the spectra of normalcy. *Oral Surg Oral Med Oral Pathol.* 58(3):272–279. doi: [10.1016/0030-4220\(84\)90052-5](https://doi.org/10.1016/0030-4220(84)90052-5).
- Pergel T, Bilge S, Demirbaş AE, Kütük N. 2023. Does the posterior bending osteotomy in bilateral sagittal split osteotomy affect the condyle position in asymmetric patients? *J Oral Maxillofac Surg.* 81(7):855–868. doi: [10.1016/J.JOMS.2023.03.014](https://doi.org/10.1016/J.JOMS.2023.03.014).
- Silva CD, Grossi ML, Araldi JC, Corso LL. 2020. Can hard and/or soft occlusal splints reduce the bite force transmitted to the teeth and temporomandibular joint discs? A finite element method analysis. *Cranio.* 41(4): 298–305. doi: [10.1080/08869634.2020.1853464](https://doi.org/10.1080/08869634.2020.1853464).
- Teltzrow T, Kramer FJ, Schulze A, Baethge C, Brachvogel P. 2005. Perioperative complications following sagittal split osteotomy of the mandible. *J Craniomaxillofac Surg.* 33(5):307–313. doi: [10.1016/j.jcms.2005.04.005](https://doi.org/10.1016/j.jcms.2005.04.005).
- Togninalli D, Antonarakis GS, Schatz JP. 2022. Condylar resorption following mandibular advancement or bimaxillary osteotomies: A systematic review of systematic reviews. *J Stomatol Oral Maxillofac Surg.* 123(6):e948–e955. doi: [10.1016/j.jormas.2022.03.008](https://doi.org/10.1016/j.jormas.2022.03.008).
- Vandeput AS, Verhelst PJ, Jacobs R, Shaheen E, Swennen G, Politis C. 2019. Condylar changes after orthognathic surgery for class III dentofacial deformity: a systematic review. *Int J Oral Maxillofac Surg.* 48(2):193–202. doi: [10.1016/J.IJOM.2018.06.008](https://doi.org/10.1016/J.IJOM.2018.06.008).