ORIGINAL RESEARCH

A 3D Finite Element Analysis of Stress on Temporomandibular Joint due to Maxillary Protraction Appliances with Varied Force Levels and Angulations

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Abstract

Aim: The aim of this study was to measure the stress distributions on the temporomandibular joint (TMJ) due to the face mask appliance using different levels of forces and different angulations.

Material and methods: A three-dimensional finite element model of the craniofacial complex was constructed from a cone-beam computed tomography (CBCT) scan of a patient, with the help of the Mimics software. The forces were applied on the hooks and the anchorage was taken from the chin and the forehead. Four different force directions were applied—0, 10, 20, and 30° from the occlusal plane with each having three different force levels, 800 g, 1000 g, and 1200 g (combined force on both sides). The stress distribution of TMJ was analyzed.

Results: The results indicate that the maxillary protraction appliance has a reactionary force on TMJ. Maximum stress was observed with 1200 g load and at the 0° angulation condition and the minimum stress was observed for 800 g load and at an angulation of 30°.

Conclusion: On the articular disk, condylar cartilage, glenoid fossa, and condyle, stresses increased with increase in load. However, with an increase in angulation for the given load, the stresses reduced gradually.

Clinical significance: The results indicate that the maxillary protraction appliance has a reactionary force on TMJ. Stresses induced by facemask appliance due to increased forces with low angulation could be a factor in temporomandibular joint disorders (TMDs).

Keywords: Face mask, Finite element analysis, Growth modulation.

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Introduction

The purpose of orthodontic intervention in children with varied malocclusion is to achieve a balanced facial profile with an acceptable occlusion.[1]

The term "growth modulation appliance" refers to different appliances designed to guide the position of the mandible or maxilla in order to transmit favorable forces to the basal bone and the dentition. These appliances are used to stimulate and redirect the functional forces to achieve changes in the craniofacial complex. For patients with a class III skeletal malocclusion, the use of maxillary protraction appliances to correct maxillary deficiency and the use of chin cup to treat mandibular excess have been documented in the orthodontic literature.[2–4] One of the appliances used commonly to treat class III malocclusion due to maxillary deficiency is the face mask.

Its conventional design was introduced by Dr Jean Delaire and it consisted of a forehead support, chin cup, and a metal frame. To protract the maxilla, the anchorage units used are the mandible and forehead.[5] Usually 800–1000 g of orthopedic force is recommended to protract the maxilla and 70–75% of this force gets transmitted to the temporomandibular joint (TMJ).[6] Hence, the effect on the TMJ must be considered when using such heavy intermittent orthopedic forces.

Use of orthopedic forces leads to a complex biomechanical response on bone. The use of the finite element method has enabled us to evaluate certain biomechanical characteristics such as stress and strains, when external forces act upon living biological structures through a simulated model.

In orthodontics, it has been used to analyze the biomechanical effects of different treatment modalities. The use of FEM in orthodontics has several advantages. It is a noninvasive technique and can measure the amount of stress and strain at any point on tissues like alveolar bone, periodontal ligament, teeth, and craniofacial bones through a simulated model.

The magnitude and direction of a force can be varied to simulate various clinical situations and since the process does not affect the physical properties of the material being studied, the study can be repeated numerous times.[7] This method is an approximation method to study the three-dimensional stress distribution and deformation of the structures on which forces are applied.

During the use of face mask, stresses are generated in the orofacial complex and TMJ when the maxilla is protracted.[1] But does this stress pattern remain the same when using different levels and angulations of forces are unknown? Hence, this study aimed

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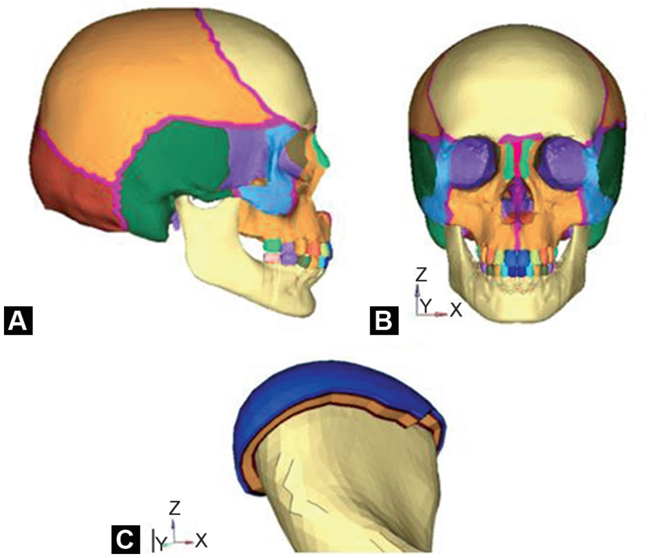
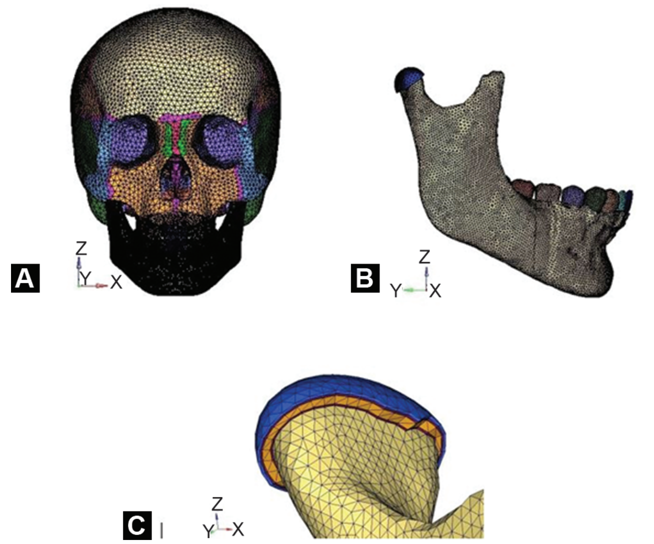


Figs 1A to C: (A) Lateral view; (B) The frontal view; (C) Modelled articular disk



Figs 2A to C: (A) Meshing of the model; (B) Meshing of mandible; (C) Meshing of the articular disk

at measuring the stress distributions on the TMJ during use of the face mask appliance using different levels of forces and different angulations.

Materials and Methods

A three-dimensional finite element model of the craniofacial skeleton was made, which included the articular disk using data from a cone beam computed tomography (CBCT) scan of a patient obtained from the archives of the Department of Oral Medicine and Radiology from the Faculty of Dental Sciences, Ramaiah University of Applied Sciences.

The digital imaging and communications in medicine (DICOM) images of the scan were selected and converted into a binary stereolithographic (STL) format. Further, this was converted into a geometric model consisting of surfaces and lines using the MIMICS software (Fig. 1). The condylar cartilage and the glenoid fossa were modeled separately (Fig. 1C). Both were given a uniform thickness of 0.5 mm according to the measurements by Hansson et al.[8] Once the surface model was obtained, it was exported to the finite element modeling tool (HYPERMESH version 13.0). Based on these 3D solid models, an FE mesh was created. The total number of nodes for the model was 87,313; the total number of elements was 378,717 (Fig. 2). The different structures involved in this study were teeth, glenoid fossa, articular disk, mandibular bone, and condylar cartilage. For assigning material properties, the articular disk was divided in to three regions, that is, anterior, intermediate, and posterior. The material properties that assigned to the model were the Young's modulus (or modulus of elasticity) and the Poisson's ratio based on previous studies[2,9–11] (Table 1). The boundary conditions were defined so as to stipulate how the model was constrained and to prevent free body motion. The model was fixed at the occipital bone region. Since this study was done to check for the stress distribution on TMJ due to the face mask and the face mask appliance uses the support of the forehead and chin, the model was fixed at the chin and forehead. Application of forces on the maxillary dentition were made into a single unit. Hooks were placed between the canine and premolars on both sides and different forces were applied from these hooks in different angulations from the occlusal plane. Four different groups were formed in this study.[1] Forces at an angulation of 0° from the occlusal plane stresses were calculated with three different forces, 800 g, 1000 g, and 1200 g.[2] Forces at an angulation of 10° from the occlusal plane stresses were calculated with three different forces, 800 g, 1000 g, and 1200 g.[3] Forces at an angulation of 20° from the occlusal plane stresses were calculated with three different forces, 800 g, 1000 g, and 1200 g.[4] Forces at an angulation of 30° from the occlusal plane stresses were calculated with three different forces, 800 g, 1000 g, and 1200 g.

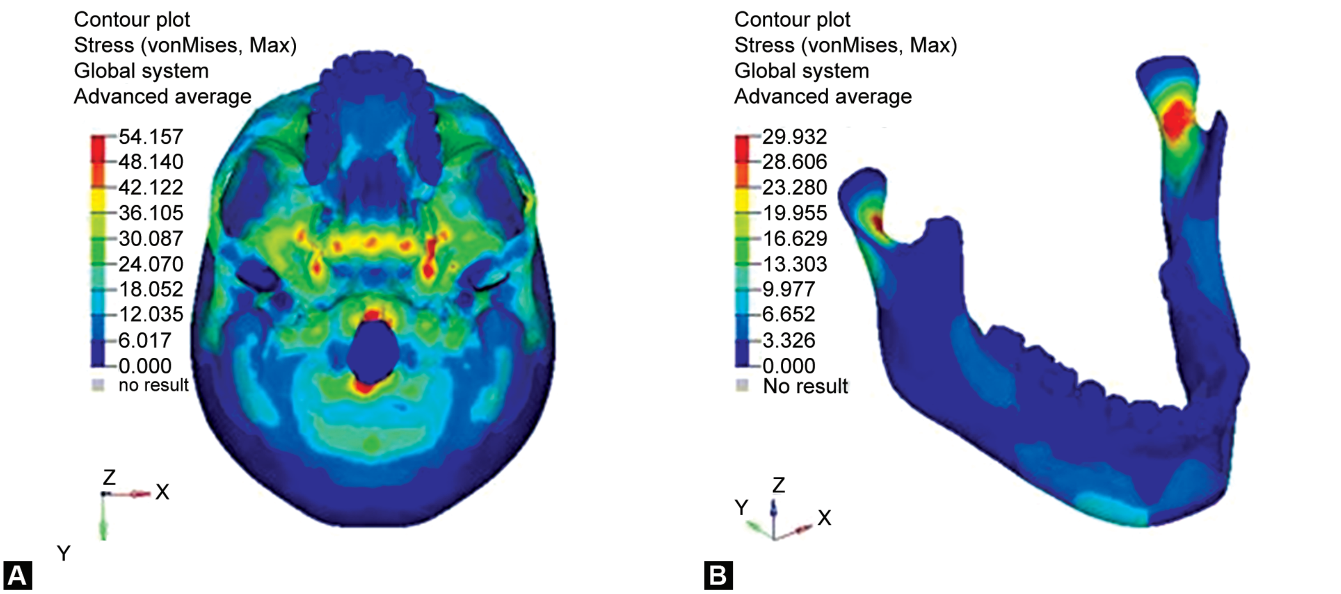
Table 1: Material properties of the different anatomic structures

	Elastic modulus (E) (MPa)	*Poisson's ratio (v)*
Condyle		
Compact bone	13,700	0.3
Cancellous bone	7,930	0.3
Cartilage layer-0.5 mm	0.79	0.49
Articular disk		
Anterior	10	0.4
Intermediate	10.73	
Posterior	9.0	
Glenoid fossa		
Compact bone	13,700	0.3
Cancellous bone	7,930	0.3

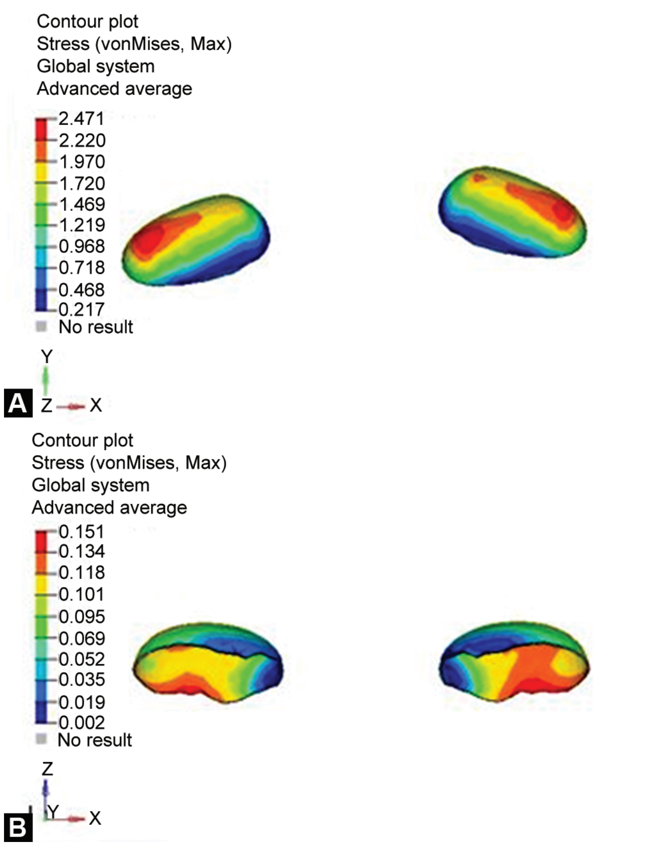
The finite element analysis (FEA) was carried out using the Ansys software version 12.1. The prepared models were processed using the FEA, and the results were visualized as von Mises stress maps (in mega pascals). The amount of Mises stresses generated in different parts of TMJ were calculated and represented with different colors.

Results

The amount of maximum principal stress and Von Mises stresses generated in different parts of TMJ were calculated and represented with different colors. Examples of stress observed on the mandible, articular disk, cartilage, and glenoid fossa are illustrated in Figures 3



Figs 3A and B: (A) Stress induced on the glenoid fossa; (B) Stress induced on the mandible



Figs 4A and B: (A) Stress induced on the articular disk; (B) Stress induced on the condylar cartilage

Table 2: Stress produced on the different structures

Force levels	*400 g per side*	*500 g per side*	*600 g per side*
Stress induced in MPa			
Group I: Stress at 0° angulation			
Condyle	30	37.56	45.07
Articular disk	2.46	3.07	3.68
Cartilage	0.152	0.19	0.228
Glenoid fossa	6.09	7.618	9.14
Group II: Stress at 10° angulation			
Condyle	29.9	37.42	44.89
Articular disk	2.47	3.09	3.71
Cartilage	0.151	0.189	0.226
Glenoid fossa	6.02	7.52	9.03
Group III: Stress at 20° angulation			
Condyle	28.9	36.13	43.5
Articular disk	2.41	3	3.61
Cartilage	0.145	0.182	0.218
Glenoid fossa	5.76	7.19	8.6
Group IV: Stress at 30° angulation			
Condyle	26.9	33.75	40.49
Articular disk	2.27	2.83	3.4
Cartilage	0.135	0.169	0.203
Glenoid fossa	5.32	6.65	7.98

and 4. In all four groups, on the mandible, the maximum stress was observed in the condylar neck region at all different force levels and angulations. On the articular disk, the maximum stress was observed at the anterosuperior region at all different force levels and angulations. On the condylar cartilage, the maximum stress was observed at the lateral aspect of the cartilage. The stress on the condylar neck, articular disk, condylar cartilage, and glenoid fossa increased with increase in force level in all four groups. The stresses decreased with increased angulations. The maximum stress was observed for 1200 g load and at an angulation of 0° (Table 2).

Discussion

There are various methods by which stress can be measured on the TMJ, such as reflection photoelasticity, FEA, viscoelastic FEA, and boundary element method (BEM). However, FEA is considered to be one of the best methods of measuring stresses suggested in the literature.[12–14] In a study done by Citarella et al., the stress analysis using the finite element method and the boundary element method was compared and it was concluded that the finite element method (FEM) method has the advantage of high versatility over the BEM method.[12] In a study done by Christophe Meyer et al., stress analysis was carried out using reflection photoelasticity. In this method, the mandible was coated with a layer of photoelastic resin and deformation was measured based on the displacement of the resin. However, this method only measured the stress in two dimensions and in a single plane.[13] Hence there is a need to measure the stress distribution in three dimensions replicating the clinical scenario, which is possible only using FEM. This method is a complex computational technique that can be used to assess solutions of boundary-value problems seen in engineering. This method makes it practical to evaluate the biomechanical components such as stress, strain, and displacements in biological structures, which arise from various types of external forces.

In this study, a finite element model was constructed for the evaluation of the stresses induced on the condyle, glenoid fossa, and the articular disc caused due to maxillary protraction appliance such as face mask with different force levels and different angulations.

The condylar position with respect to the glenoid fossa and articular eminence is one of the etiologic factor of temporomandibular joint disorders (TMDs). Hence, any changes in the position of the condyle and thereafter any biomechanical alterations of the articular disk during face mask therapy may lead to internal derangement of the TMJ.

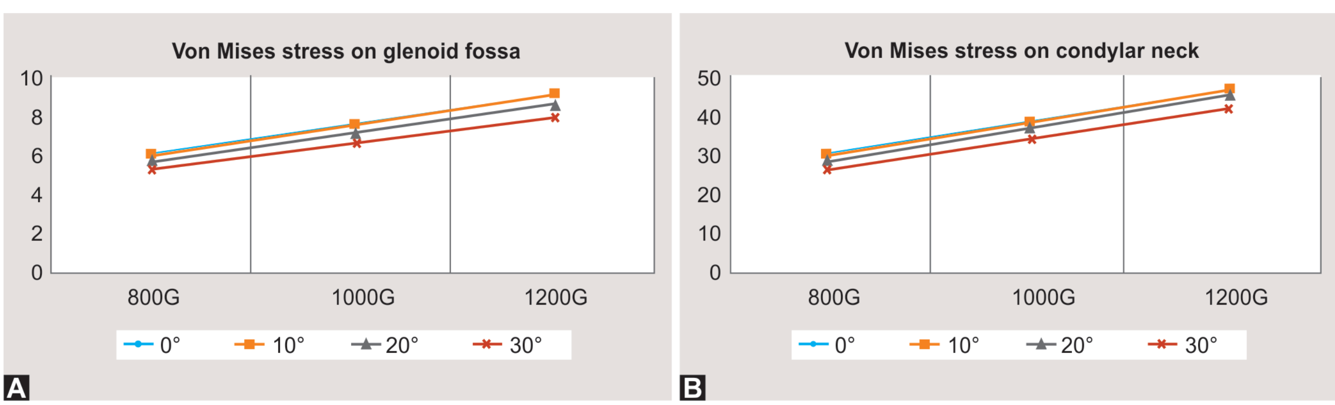
The effect of chin cup therapy on the TMJ has been assessed in numerous studies done by Deguchi et al. in 1998, Gökalp et al. in 2000, and Gökalp and Kurt in 2005.[15–17] However, only in a limited number of studies the effect of face mask therapy on the TMJ has been investigated. It is a well-known fact that for the treatment of class III malocclusion due to maxillary deficiency, the face mask is the device most commonly used. The Face mask applies anteriorly directed force on to the maxilla and derives its support from the chin and the forehead. In a study by Grandori et al. about maxillary protraction, the force that was generated by the chin part of the face mask was ignored whereas the force transmitted to the TMJ by the face mask is reported to be 70–75% of the protraction force applied on the maxilla.[18] Yu et al. in 2007 evaluated the effects of maxillary protraction with and without rapid maxillary expansion and reported that ignoring the force transmitted to the chin by the face mask was a drawback of the study and suggested that this point should be taken into account for the accuracy of further studies.[19] Hence, in this study force generated by the face mask was simulated and its effect on TMJ was evaluated.

During any orthopedic therapy, the optimal force is considered to be the lowest force applied for the least duration that produces the greatest skeletal movement and least dental movement.[20] In orthopedic orthodontics, finding the optimum force leading to adequate results has always been an issue. Studies done by Tanne et al. has shown that differences in magnitude, direction, and duration of force can lead to different patterns of displacement and distribution in maxillofacial structures, which leads to unexpected results and different stress patterns.[21]

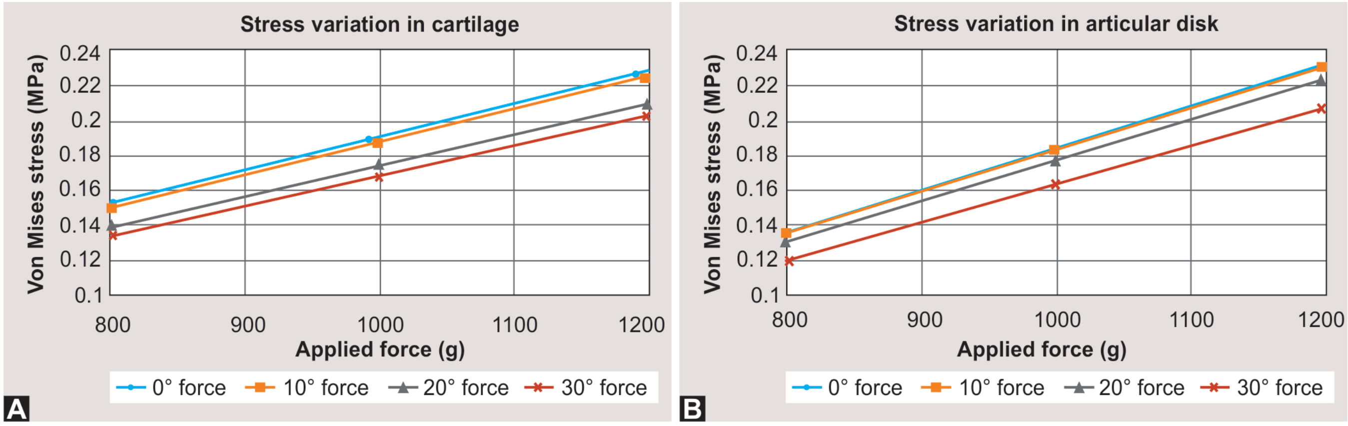
In this study, three different force levels of 400 g, 500 g, and 600 g per side were used. Numerous studies have used different force levels of face mask therapy, which range from 300 g to 500 g per side. A study by Vaughn et al. in 2005 used 400 g of force;[22] similarly, a study done by Tortop et al. also used 400 g per side as the force value.[23] A study done in 2000 by Saadia and Torres used a force value of 395 g per side.[24]

In this study, four different angulations of 0°, 10°, 20°, and 30° were used to assess the stress distribution. Tanne and Sakuda in 1991 proposed that the direction of the force should be parallel to the occlusal plane.[21] Keles et al. used a force vector angulation 30° from the occlusal plane.[25] Tortop et al. used a force vector angulation 20° from the occlusal plane.[23] In this study, the maximum stress was observed on the anterior region of the condylar neck, which was similar to a study done by Karamanli et al. in 2017 in which the biomechanical effects of face mask therapy on the craniofacial complex was evaluated using FEA. Simulation was performed using a three-dimensional FE model. In the simulation, the magnitude of the force used was 750 g per side, and the force direction was 30° forward and downward to the occlusal plane. It was found that stress distribution was higher on the lower edge of the chin and condyle necks.[26] The maximum stress for the condyle, glenoid fossa, articular disc, and cartilage was observed at an angulation of 0° with 1200 g load. The least stress was observed at an angulation of 30° with 800 g load.

In this study, for a given angle, the stress increased with the increase in applied force (Figs 5 and 6), which was similar to the study done by Liu et al. in 2013 in which stress distribution was analyzed from forces generated by maxillary protraction appliance. A 3D model of maxillary protraction device was established and different forces from 3 N to 6 N at an angulation of 37° from the occlusal plane was applied at the chin to measure and analyze changes in stress and displacement in TMJ using the finite element software. At the same angle, the stress in the



Figs 5A and B: (A) Maximum Von Mises stress on glenoid fossa; (B) Maximum Von Mises stress on condylar neck



Figs 6A and B: (A) Maximum Von Mises stress in cartilage; (B) Maximum Von Mises stress in articular disk

head and neck of the condyle and articular fossa increased with the applied force. Hence, it was concluded that stress in the TMJ increased with applied force at the same angle.[27] In the present study, stress on the TMJ decreased when the angle of the force direction increased (Figs 5 and 6), which was in agreement to a study done by Dong et al. in 2013 in which the influence of different reactive force direction of protractions on TMJ was analyzed by the FEM method. The force pattern of the maxillary protraction appliance was imitated and the force of 5 N was applied on the chin and the direction of force was varied from 22° to 49° relative to the occlusal plane. The stress distribution on TMJ was analyzed. The contact stress on the maxilla decreased with the angle of the force direction increased from 22° to 40°. The stress on the condyle decreased when the angle of the force direction increased. Hence, it was concluded that stress on the TMJ decreased when the angle of the force direction increased.[28] The probable reason for this could be that the reactionary force (upward and backward force exerted at chin), when the angle is increased, is parallel to the long axis of the mandible (body and ramus together) compared to the reactionary force that will be directed only backward in case of 0 angulation. The possibility of the face mask being a deleterious factor for the TMJ should also be evaluated by the intensity of stresses added by this appliance. In this study, the maximum stress for the condyle along with glenoid fossa, articular disc, and cartilage was less than the elastic limit of the structures; however, it was found to be greater than the forces generated by the normal functioning of the jaws. Hence, stresses induced by the face mask appliance could be a factor in TMDs.

In this study, finite element models were used to simulate only the force from the maxillary protraction appliance but not from the stretch of soft tissues such as muscles, ligaments, and skin. This was an *in vitro* simulation of the clinical situation and in the actual clinical scenario, anatomical variations in the morphology of the condyle, glenoid fossa, and mandible should be accounted. These are the limitations of this study.

Conclusion

A pattern of stress is created, which indicates that facemask therapy for maxillary protraction has a reactionary force on the TMJ. On the articular disc, cartilage, glenoid fossa, and condyle stresses increased with increase in load. However, with increase in angulation for the given load, the stresses reduced gradually. The maximum stress was observed for 1200 g load and at 0° angulation condition.

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