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# A musculoskeletal Finite Element Study of a Unique and Customised Jaw Joint Prosthesis for the Asian Populace

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**Abstract:** The stress concentration for a unique temporomandibular joint prosthesis was evaluated using finite element analysis in the present work. This study intended to validate temporomandibular joint prosthesis design specific to Asian population. Total joint replacement is a complicated procedure and surgery can cause numerous complications such as hardware failure, cleft, contamination or facial immobility. Hence, it is imperative to study stresses acting during jaw movement. A three-dimensional static structural finite element approach was followed. The study reflects on even stress distribution, with least detrimental effects to human natural joint. Thus, the design efficiency is validated and also helped in analysing medical ramifications for actual temporomandibular joint surgery.

**Keywords:** Finite Element Analysis, Biomedical devices, prosthesis, human jaw, computational analysis, Asian population

## 1. Introduction

Temporomandibular joint (TMJ) is a crucial element of craniomaxillofacial complex having rotation as well as translation and is responsible for jaw activity, mastication and speech. The TMJ is afflicted with an array of diseases but surgical intervention is the least preferred relieving procedure. Documented research surmises that TMJ disorders affect more than 25% of world population, of which merely 5% need implant surgery. Disorders such as tumours, degenerative joint disease, developmental irregularities, ankylosis and trauma are deterrent to normal functioning of TMJ. It is imperative to have comprehensive awareness about biomechanical functionality of prosthetic material as well as its suitability and adherence to the bone and muscle. This can be successfully assessed by determining the implant load and stresses on the natural joint upon placing the TMJ prosthesis.

Alloplastic prosthesis has a probable benefit as compared to conservative methods for TMJ total joint reconstruction by expediting the functional restoration and minimizing the surgical duration as well as discomfort. A recent study by Mazzocco et al<sup>2)</sup> observed that custom TMJ devices are reliable replacements to stock prostheses as the masticatory muscle in both unilateral and bilateral condition for varying loads can

bear fluctuating stresses for longer periods resulting in Osseo-integration as observed in FEA studies.

On the other hand, TMJ intravenous surgery using metal-plastic prosthesis has few disadvantages too, such as high cost, material incompatibility, prosthesis failure, due to wear, corrosion, displacement, screw fracture or loosening. In fact, as per literature 15.9% of all the reported complications are due to prosthesis failure. Kashi et al<sup>4)</sup> performed FEA to appraise the stress concentration in Food & Drug Administration, USA (FDA) approved TMJ implant (TMJ Implants, Inc., CO), bone-implant-bone conjugate, to correlate the observed stresses with varied bone conditions and implant materials. Highest stresses were observed in screw hole location near to condyle in this study. A failed prosthesis design can put disproportionate load on the mandible leading to intolerable distress and discomfort as it influences the articular surface and conjoined muscles. The quantity of screws used for securing the prosthesis as well as its location also has significant influence on pain and stress distribution across mandible. Hence, it is imperative to validate any new or innovative prosthesis design through finite element analysis to avoid any failure possibilities and occurrences.

The present study has taken help from literature<sup>29)</sup> to study its prosthetic model for finite element analysis under varying loading conditions. Tanaka et al. has

discussed in generous detail about the biomechanics of temporomandibular joint in which FEA studies were conducted on human jaw joint. The loading conditions and pre-requisites for 3D modelling and analysis in those studies were utilized as a base model for the unique TMJ design in the present work. Few researchers<sup>22)</sup> emphasized on the importance of evaluating bone and muscle conditions while designing dental implants or prosthesis wherein Chakorborty et al took in a specific case study recently. Merema et al.<sup>23)</sup> discussed about the lack of consensus on specific conditions for conducting FEA studies on TMJ implants and suggested that a comprehensive and directional outlook is necessary for validation of such studies in the field of TMJ TJR in the view of insufficient data available in the past studies.

The present study aimed at developing a musculoskeletal jaw model along with placement of uniquely designed TMJ prosthesis unilaterally and bilaterally to study the impact of screw location, joint design or stress pattern across jaw.

## 2. Materials and methods

The TMJ prosthesis parts – fossa and condyle were designed in Solid Works 2012 version SP0.0. A musculoskeletal jaw model was constructed using 3D SLICER 4.10.2. The three-dimensional (3D) mesh model development of prosthesis placed on jaw model was carried out in ANSYS software (version 18). Surface boundaries were established for fossa, mandible, condyle and all the related musculature. The muscles of mastication were represented through their force magnitudes provided and used from literature as shown in Table 1. The jaw model was defined in x axis laterally, in y axis posteriorly and in z axis superiorly. The jaw model was aligned in Frankfurt plane with x-y plane, which coincides with occlusal plane. This helped to rotate the model in the direction of bite force. The bite force range used in the present study was 200-1000 N. The range and criterion for the present study was chosen from literature. Ingawale et al<sup>31)</sup> explained and discussed the temporomandibular joint anatomy and its biomechanics (Indian origin TMJ included) in the book titled Human Musculoskeletal Biomechanics. It extensively details the various methods and techniques as well as hypotheses utilized in study of biomechanics of human TMJ. Muscle mastication forces along with their reaction forces were active during analysis which was applied on the mesh model (Fig. 1 and Fig. 2) using static structural approach.

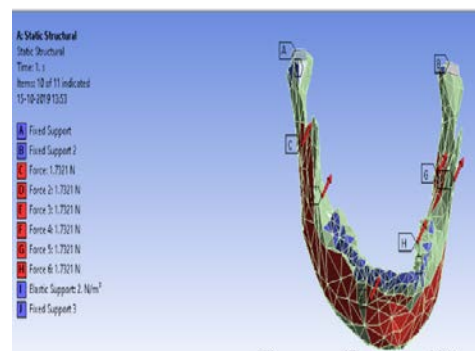


Fig. 1: Muscular forces and their reaction acting on the joint

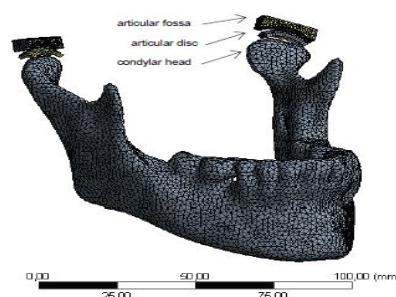


Fig. 2: Numerical Mesh model as obtained after conversion from digital to mesh model

### 2.1 TM joint design

The metal-plastic prosthesis assembly has two parts- upper jaw fixation called fossa implant made using Ultra High Molecular Weight Polyethylene (UHMWPE) and lower jaw fixation – mandibular implant with a condylar head. The fossa implant has an inner cavity or crater to accommodate translational and rotational movements of condylar head attached to mandibular implant. It has four holes (1-1.5 mm  $\varnothing$ ) for screwing fossa component on zygomatic arch. The inner cavity of fossa component is designed in such a way that it will provide an offset angle of 10-12° for an initial pure rotation of condylar head inside the cavity and then convert it into translational/ rotational movements for different functions of jaw. The mandibular implant with condylar head has been constructed using a grade 5 Titanium (Ti) alloy. The condylar head is as a spherical shape with flat top, and a small cylindrical neck attaching it to a concave mandibular plate with 10 holes for screwing the implant on lateral periphery of mandibular ramus, to which implant is placed parallel. The mandibular implant is custom-designed and 3d printed to the actual shape, curvature and position of ramus of the mandible.

Tetrahedral solid elements have been used for constructing finite element model of mandible jaw with alloplastic prosthesis and supporting musculature. Boundary conditions have been assigned to the elements in this study from literature as shown in Table 1. A mesh has been created of all anatomical and prosthetic structures. Von Mises theory has been used for stress analysis as it has more intricate view about principal

stress distribution. Von Mises principle has more elaborative results for ductile materials.

Table 1: Boundary conditions used for finite element study of unilateral and bilateral prosthesis

Load Condition	Resultant Force (N)		Location of Max Von Mises Stress	
	Left	Right	Unilateral	Bilateral
Low	200	200	Equal on both condyle	Equal on both condyle
Unbalanced	250	400	Right condyle with natural contra-lateral joint	Equal on both condyle
High	1000	1000	Right condyle contra-lateral joint	Equal on both condyle

The TMJ prosthesis was designed using computed tomography (CT) scan images from the library of 3D Slicer for a human skull and constructed using UHMWPE and Ti Grade 5 alloy for fossa, condyle and mandibular implant. The present studies discuss preliminary design prototype, hence the CT scan data used in this work has been taken from an open source platform 3D SLICER. The digital CT scan images are anonymous, irreversible and unidentifiable and do not reveal any patient information. As far as patient informed consent is concerned, according to Helsinki declaration, various national (ICMR) and international (HIPPA) guidelines<sup>31-32</sup>, the research with no risk or minimal risk of identification of patient data can be conducted without any informed consent from the patient. 3D model was designed using SolidWorks by Dassault Systèmes following which virtual total joint replacement was carried out.

## 2.2 Design and conception of fossa implant

The fossa eminence of the TMJ prosthesis was designed and modelled in 3D from CT scan data, using UHMWPE. In the FE model, material properties of same were used. The centre of application of forces was condylar head inside fossa eminence. The stresses inside fossa eminence were calculated and observed. The size of the element was 1.674 mm. The number of nodes for used for constructing fossa was 20000 with 8567 elements. The assembly was constructed with fossa and mandibular implant and simulated in SolidWorks platform.

Fossa with UHMWPE as its material and mandibular implant with Ti Grade 5 alloy as its material were analysed by application of forces on the joint. The model was assigned material properties for different components, imported from the SolidWorks Database or

from literature. Four screws of Ti Grade 5 alloy were used with 2.5-3 mm diameter. Von Mises Theory was applied for studying stresses on the joint prosthesis after application of screws.

The forces along with magnitude and direction<sup>4)</sup> (values taken from literature) were assigned to the model using custom made plane method. The amount of stress and strain on the prosthesis depends majorly on the forces of mastication. All these forces were simulated in the FE model during this study. Total of 12 resultant forces were accounted for equally on both sides of the jaw, where the magnitude of muscle force was divided equally among 12 resultant forces. A sliding contact ( $\mu$  as 0.1) was assigned for connection between condylar-fossa eminences.

## 3. Results

The summary of properties of human jaw, condyle prosthesis, and fossa eminence was given in Table 2. The reaction forces in screw affixed regions, after mastication was 650 N, 375 N and 110 N. The reaction forces in condylar head periphery had a resultant magnitude of 1034 N. During mastication, all the muscle forces exerted a stress of  $5.76 \times 10^6$  N/m<sup>2</sup>, at condylar head of contralateral natural joint for unilateral joint at high loading of 1000 N. For the same boundary conditions, a stress of  $3.076 \times 10^6$  N/m<sup>2</sup> for a bilateral joint.

Von Mises stresses are reported for unilateral TMJ and bilateral TMJ for four different loading conditions i.e. normal loading, unbalanced occlusion, bruxism and clenching. As expected, clenching created high stresses around the disc surfaces and higher stresses are observed in bilateral TMJ in all the four loading conditions.

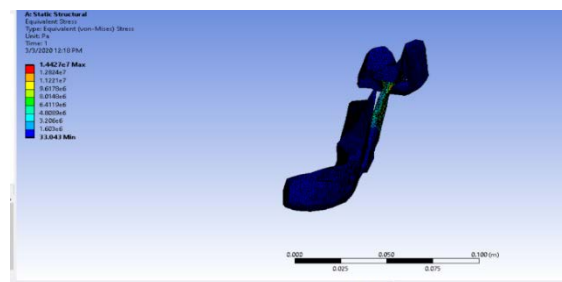


Fig. 3: Finite Element Analysis (FEA) with Von Mises stress distribution in unilateral alloplastic joint for 200 N

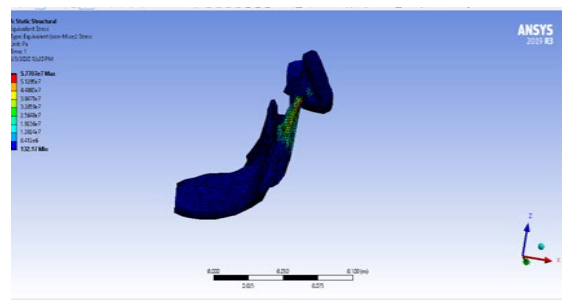
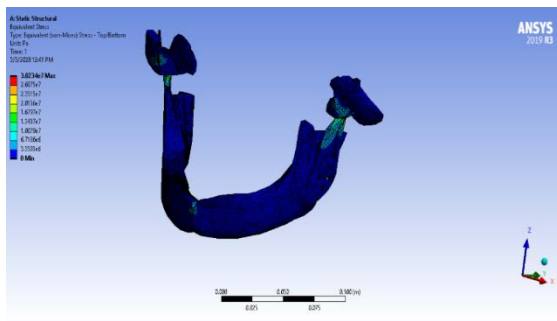
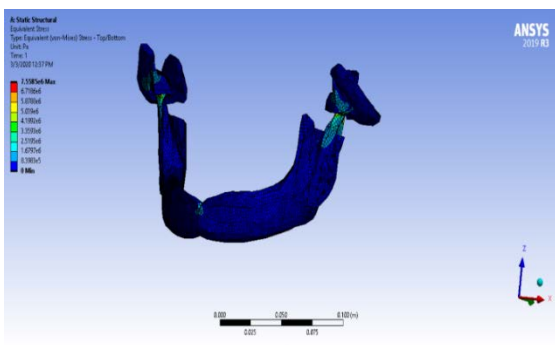


Fig.4: FEA showing Von Mises Stress distribution in unilateral alloplastic joint for 1000 N



**Fig. 5:** FEA showing Von Mises stress distribution in bilateral alloplastic joint for 200 N



**Fig. 6:** FEA showing Von Mises stress distribution in bilateral alloplastic joint for high loading condition of 1000 N

Von Mises stresses correspond to tissue strains rather than contact pressures, hence in case of bilateral TMJ, stresses are higher. The present study gives an all-inclusive investigation of all the loading conditions that have a compounding effect on functioning of TMJ prosthesis.

Table 2: Material Properties for bone, cartilage, titanium and UHMWPE

Material	Young's Modulus (GPa)	Poisson's Ratio
Cortical bone	17	0.3
Teeth	50	0.25
Cancellous bone	0.5	0.3
Cartilage	0.006	0.49
Titanium	110	0.3
UHMWPE	0.45	0.4

#### 4. Discussion

The present work intended to develop a human jaw model in three dimensional showing all bone joint elements and to simulate the placement of novel TMJ prosthesis design unilaterally and bilaterally to assess the stress distribution when the prosthesis was subjected to function. The finite element study comprised of analysis of various bio-mechanical characteristics of TMJ prosthesis. It found maximum values for principle stress

distribution for various loading conditions at condyle ramus region, fossa condyle interface, screws placed at mandible ramus. After the finite element model simulation, all results and inferences were thoroughly analysed.

The inferences from the present study suggests that for all the varying loading conditions, unilateral joint prosthesis has lower stress values as compared to bilateral prosthesis. The stress is more concentrated in the condylar-fossa interface as compared to other regions on the mandible. Higher values of stress were found at screws fixed parallel at ramus plate. The main principle behind fixation of screws and their amount is based on literature evidence that even three screws can provide sufficient stability to the prosthesis. Also, the stress levels in cortical and cancellous bone were determined by the no. of screws and their position. Implant design, geometry and its adherence to the shape of human mandible along with prosthesis materials highly majorly contributes in determining the biomechanical behaviour of jaw as well as the prosthesis. These factors have been thoroughly studied in Finite Element Method (FEM) as screw positions and amount significantly affects jaw behaviour and stress pattern in prosthesis. This helped in introducing more design modifications in our novel prosthesis joint to avoid stress concentration and implant failure.

Total joint prosthesis design with varied screw placements has distinctively focused studies in literature for its clinical and functional outcomes. TMJ works conjointly with the contra lateral side and any unenviable situation can cause disastrous ramifications on both joints. Various researchers have discovered notable changes in the masticatory function, movements and forces in patients with unilateral and bilateral TMJ replacement surgeries. A literature study based on kinematics of 3d model suggested that whenever unilateral prosthesis placed on one side, the stress pattern on the contra lateral joint varies revealing lack of translational motions, mandibular function as well as motions of contra lateral joint. To avoid these adverse effects on current design under study, the cavity under fossa eminence in which condylar head moves, has been given an indent angle for the initial movements of prosthesis side, mimicking the motions of contra lateral joint. This automatically reduces stress on the contra lateral natural side of jaw.

The patients who required unilateral total joint replacement of TMJ were evaluated by Perez et al<sup>1)</sup>. It has been observed from the study that unilateral joint has an improved functionality, clinical as well as kinematic and an increased probability of not requiring Total Joint Replacement (TJR) for a healthy contra lateral joint. But there is a probability (30%) of requiring TJR for a contra lateral joint with previous surgical history. In the current study, no stress or strain was observed on contra lateral joint during unilateral TJR or on the adjoining natural



mandible during bilateral joint thus it can be hypothesized that for a unilateral prosthesis TJR on the proposed design, there is no need for contra lateral TJR later on, and for bilateral prosthesis TMJ TJR, the stress and strain observed is also not worrisome.

Auckland et al.<sup>3)</sup> observed resultant joint force of 102.4 N and 83.9 N on the unilateral prosthetic TMJ and contralateral natural joint respectively in their finite element analysis. The hypothesis stated in their research work proven valid when the orientation of alloplastic prosthesis affects the stress distribution across screws affixed regions. The contact stresses and strains were observed anteriorly beyond 15 degrees of rotation in the condylar component only when quantity of screws was increased to stabilize the prosthesis. Contrarily in the present work, the prosthesis joint was placed parallel to the ramus and low stress concentration with required stability was achieved using a smaller number of screws as endorsed in the previous studies.

Bhargava et al.<sup>18)</sup> evaluated the stress and strain distribution using finite element analysis for DARSN unilateral temporomandibular joint and its effects on contralateral natural joint. The study contributed to the hypothesis that unilateral prosthetic joint causes minimal adverse effects to the contralateral natural joint.

Maurya et al.<sup>5)</sup> investigated experimentally and computationally about an additive manufacturing component to enhance its mechanical properties, ABS is used for making biomedical prototypes using FDM techniques. Reinforcing a new component can increase the life of biomedical device and assist in better surgical performance. This study helped us to identify if using additive manufacturing technique for surgical, dental or biomedical devices is advisable or advantageous in vitro before performing actual surgical procedure.

Mamidi et al.<sup>6)</sup> shared few concerns related to TMJ surgery failures. It was expressed that further research is needed for implant design which must include TMJ components and their materials' ability to withstand high concentration stresses, under severe or maximum loading conditions. According to Memon et al.<sup>7)</sup>, it is imperative to conduct finite element analysis of prosthesis and implants which can reflect on complex geometry of implant and its biomechanical properties. Antic et al.<sup>8)</sup> presented a brief study on morphology of bone and muscle action in human jaw, which can be useful in implant design and analysis. For a TMJ prosthesis articulating as a spherical ball inside the fossa eminence, the wear rate of UHMWPE was determined to be quite low by Van Loon et al.<sup>9)</sup> thereby assuring its safe application in the patients.

A major point of concern while conducting FEA studies in the past<sup>10-12), 21)</sup> was to understand how to extract 2D model or 3D model from CT scan or MRI data and how to conduct dynamic simulations for the same. Mackerle<sup>13)</sup> discussed and presented a comprehensive bibliography about finite element

analysis and simulations in dentistry which helped to find correlations among FEA's in the recent past on prosthetics, dental implants and other dental devices. Numerous researchers worked on the design and development of TMJ implants, its analyses, testing's, clinical trials and their outcomes to outline the importance of TMJ TJR in the recent decade<sup>14-20)</sup>.

Boccalatte et al.<sup>24)</sup> discussed in a recent paper about pre-operative and post-operative conditions in a TMJ prosthesis and how it can help to validate the FEA studies conducted virtual pre-surgery. This can help in expediting clinical trials and extrapolate their outcomes quickly for a custom TMJ prosthesis.

Ismail et al.<sup>25)</sup> discussed a feasible method for reconstruction of 3D model which can assist in FEA studies on local stress concentrations on cortical bone, cancellous bone and muscles interface for an improved and innovative implant design. Rodriguez et al.<sup>26)</sup> conducted wear and fatigue analysis using FEA technique on TMJ implant to understand about bone and muscle compatibility with Titanium and UHMWPE. L.G. Mercuri<sup>27)</sup> emphasized on thorough and extensive research about clinical trials and their outcomes, in-vivo and in-vitro studies, implant design failures, and other reasons pertaining to increase the life of a prosthesis. G. Bullis<sup>28)</sup> has stressed on investigations about stress concentrations in dental implants which can adversely affect prosthesis due to unbalanced loading conditions.

Kashi et al.<sup>30)</sup> recently discussed about certain retrospective and prospective studies on TMJ implants, the new custom-made prostheses, their success and design failures. The computations carried out in the present study doesn't show any implant failures at high loading and force of 1000 N during clenching and higher stress concentrations but before drawing any conclusions on effectiveness of the design and implant it is imperative to conduct expansive in-vitro studies so as to avoid any implant failures, to increase the life of an implant and to achieve cost-cutting with new technology as an overall impact.

## 5. Conclusion

As observed from the obtained results, for all the varying loading conditions, unilateral joint prosthesis has lower stress values as compared to bilateral prosthesis. It has been also found that the stress and strain distribution is distinctively lower in these anatomical designed prosthesis in comparison to the commercial TMJ implants. Moreover, it has been observed that in customized TMJ prosthesis, the mandible can move with even less efforts from the muscles.

In conclusion, customized TMJ prosthesis is preferable in TMJ total joint replacement since it can provide more or less same amount of displacement in opening and closing of the jaw which will in effect produce lesser stress on the mandible. This will also

subsidize for less muscular force interaction for lower jaw movement.

Although the present work is limited to the scope as this is a computational study and experimental validation and clinical trials are imperative for checking the feasibility of design, suitability and biocompatibility of prosthesis.

Additionally, the present study has not taken actual patient data for conclusive studies of human TMJ. The efficacy of design and computational studies needs to be validated using actual TMJ patient CT data for customization of prosthesis.

The computational study in the present work has been validated from the literature. The following table (Table 3) provides a brief comparison of present work with relevant studies from literature:

Table 3: Comparison of present finite element study of unilateral and bilateral prosthesis with relevant literature

S No.	Type of loading	Maximum Von mises stress (pa)			
		Ingawale et al <sup>31)</sup>	Other Studies	Unilateral	Bilateral
1.	Balance d Occlusion	0.884e+05	0.35e+06	1.46e+06	2.3e+06
2.	Clenching	1.10e+06	1.68e+08	2.7e+07	3.5e+07

It can be inferred constructively from the results and discussion in the present study that these prostheses can be designed and manufactured by developing new methods of manufacturing such as 3D printing thereby providing necessary customization to the prosthetic replacement.

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### Approval and Consent

The present work is a preliminary design studies on developing a prosthesis prototype. The authors would like to inform that the data and medical images used in this study are completely unidentifiable, anonymous and irreversible, in compliance with ICMR and HIPPA guidelines<sup>32-33)</sup>.

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