I|J|A|M|B
INTERNATIONAL JOURNAL OF ADVANCES IN MEDICAL BIOTECHNOLOGY

Finite element analysis of temporomandibular joint: effect of detachment of the lateral pterygoid muscle

Anita G. Mazzocco[1]*; André I. Jardini[2]; Elifas I. Nunes[3]; Rubens Maciel Filho[4]

Corresponding author: E-mail address: anitagaia.mazzocco@gmail.com

Abstract: In biomedical engineering field, Temporomandibular joint (TMJ) is considered as a bi-component joint composed by fossa and condyle. It is considered the most active human joint and it performs daily activities such as speaking and chewing. Due to cyclic loading, TMJ disorders impair TMJ function so that it is necessary to replace the natural joint with an alloplastic prosthesis TMJ orthopedic prosthesis are made of metal alloys and ultra high molecular weight polymers. According to the literature, TMJ replacement surgery is commonly performed worldwide achieving good outcomes. However clinical outcomes point out that TMJ prosthesis present reduced joint kinematics with a limited translational mobility compared to natural joint. In case of unilateral TMJ replacement, this result generates a unilateral hipomobility and a contralateral overload. According to previous studies, this is caused by lateral pterygoid muscle detachment during condylectomy of replacement surgery. To investigate this phenomenon, this study use computational simulation with Ansys software. Finite element analysis is performed with the aim of evaluating effect of unilateral and bilateral pterygoid muscle detachment on mechanical behaviour of a natural human mandible subjected to molar and incisal bite.

Keywords: Temporomandibular Joint. Finite Element Analysis. Ansys. Lateral Pterygoid muscle.

Introduction

Temporomandibular Joint (TMJ) is a bilateral joint that connects mandibular bone to temporal bone. TMJ is a diarthrodial joint composed by condyle, at mandible extremities, and glenoid fossa, at temporal bone. The main TMJ function is to perform chewing and speaking activities so that TMJ diseases impair normal daily activities and have a psychosocial impact on life of individual (1)pain duration, psychological impairment and demographic characteristics. Methods A total of 75 patients with TMD and 75 healthy controls were recruited. The short version of Oral Health Impact Profile (OHIP-14. The study published in 2017 by Lotesto (2) revealed that TMJ replacement surgery is commonly performed internationally with an high success rate. TMJ replacement surgery is the end-stage solution to treat TMJ disorders after previous conservative surgical treatments (3). The two most implanted TMJ replacement devices are TMJ Concepts custom-made system and TMJ Biomet stock system. TMJ Concept is patient-fitted device, manufactured from Computed Tomographic (CT) data of patient, while TMJ Biomet presents different sizes to be adapted to patient anatomy. Both devices are bi-component systems replacing condyle and fossa components. Condyle component is made of metallic alloy (Ti-alloy or CoCr-alloy) and fossa component is composed of metallic mesh and UHMWPE, in case of TMJ Concepts system, or entirely made of UHMWPE for TMJ Biomet system. The history of use of these TMJ replacement devices is around 20 years so that several clinical studies have been carried out. Recently, Zou et al. [(4)] realized a review study about postoperative outcome of TMJ replacement. According to collected data, stock and custom-made TMJ replacement systems showed similar postoperative results. Clinical outcomes detected a relevant decrease of pain factor and a remarkable mouth opening index increase of about 10 mm, which improves the patients' quality of life. However, analysis of TMJ prosthesis kinematics has shown poor results of mandibular lateral excursion and protrusion [(5,6)]. So that, compared with natural TMJ, TMJ prosthesis perform purely rotational pattern, losing translational motion. In case of unilateral replacement, this effect induces a unilateral hypomobility and a contralateral hypermobility, so as to overload the natural contralateral TMJ. According to literature, this lack is likely related to the detachment of lateral pterygoid muscle due to condylectomy during replacement surgery [(4,6,7)].

TMJ natural mobility is generated by condylar movement of condyle against glenoid fossa [(8-10)]. TMJ kinematics is considered complex because the condyle performs translation and rotation movements on the 3 conventional planes. Moreover, direction and amplitude of TMJ mobility are determined by the shape of articular surface, i.e. fossa and eminence, and by the force exerted by masticatory muscles. Therefore, the combined action of masticatory muscles generates the mandibular movements of opening and closing, of protrusion and retrusion and of lateral excursion, which gives rise to the cycles of chewing and speaking. A technique commonly used to evaluate mechanical behavior of TMJ replacement is computational simulation using Computer Aided Modeling (CAM) software [(11)]. This computational simulation is a Finite Element Analysis (FEA) of mandible computational model subjected to masticatory muscles forces. FEA results inform on TMJ mechanical response, quantifying and characterizing stress and strain generated on mandible computational model. In this study FEA is performed in case of a unilateral bite, at incisors, and bilateral, at molars, with the action of lateral pterygoid muscle and without it, with the aim of evaluating the effect of this muscle on stress and strain distribution on mandibular bone.

Materials and methods

Mandible computational model is created from CT data. At first, CT-data in DICOM format is segmented with Invesalius software (CTI Renato Archer, Brazil), which generates a STL file. Segmentation technique uses threshold to separate bone structures from other biological tissues and produces a surfaces model of mandibular bone. Surfaces model is then transformed into a volumetric model with CAM software, such as Solidworks (Dassault Systèmes, France) and Magics (Materialise, Belgium).

[1]Faculty of Chemical Engineering, Campinas State University, Campinas (SP), Brazil.
[2-4]National Institute of Biofabrication (INCT BIOFABRIS)Campinas State University, Campinas (SP), Brazil.
[3]Medical School, São Paulo State University (Unesp), Botucatu (SP), Brazil.

Received 10 November 2019; Accepted 11 December 2019; Available online 10 February 2020.
DOI: https://doi.org/10.25061/ijamb.v3i1.58

CAM software corrects superficial imperfection and creates a refined solid model of mandible, generating a STP file. Finally this file is transferred to Ansys Workbench software (Ansys INC, USA) where FEA is performed.

Finite Element Model (FEM)

Finite Element Model (FEM) of mandible is created in Ansys Workbench by discretizing solid model into linear tetrahedral elements (14628 nodes and 63112 elements) and modeling with cortical bone property. Cortical bone is considered an isotropic and linear elastic material with an elastic modulus of 13 GPa and a Poisson ratio of 0.3 and characterized by density of 1950 kg/m3 [12,13]. Bites simulated are bilateral Incisor bite (INC) and unilateral Molar bites on Right (RMOL) and Left side (LMOL). In unilateral molar bite working side and balancing side are distinguished. Thus, in RMOL case the working side is on right and the balancing is on left, and vice versa in LMOL case.

Figure 1a shows FEM with external forces and boundary conditions applied. Model geometry is modified on condyle and dental parts to apply boundary conditions. Thus, model is fixed on bite point in three directions, as fixed support, and condyle heads are vertically constrained, so that they can translate on x and y directions [14]. To simulate bite loading forces of masticatory muscles are applied to FEM (Table 1).

Data of muscles insertion areas derived from Hylander book [8] and amplitude and direction of forces from Korioth model [15]. To evaluate the effect of lateral pterygoid muscle on TMJ mechanical behaviour, FEA of three bite loading is performed with lateral pterygoid and without it, as follows: Case A): lateral pterygoid on both side; Case B): no lateral pterygoid; Case C): lateral pterygoid on left side; Case D): lateral pterygoid on right side.

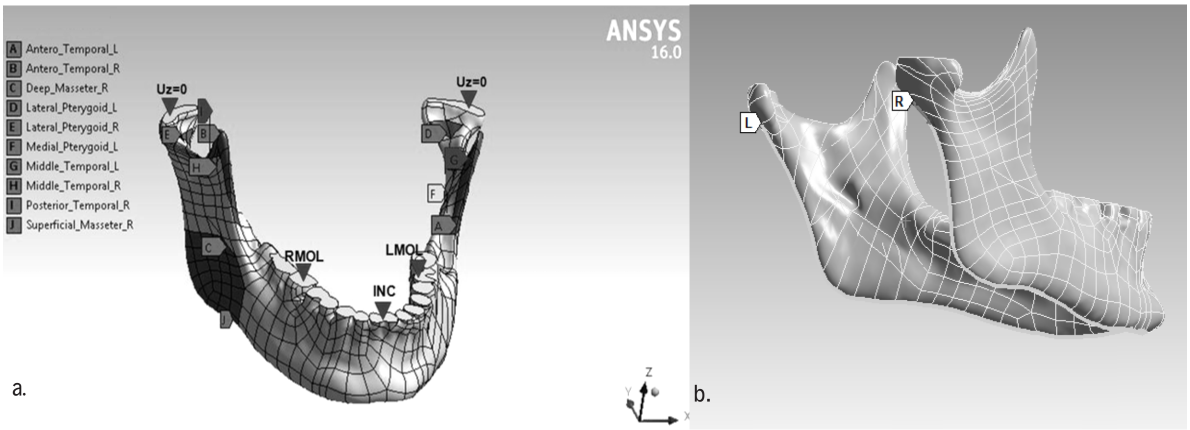

Figure 1 – a) FEM created in Ansys Workbench with applied muscular forces and boundary conditions. b) Control line to calculate minimum principal strain from right to left condyle.

Muscles	**Unilateral Molar Bite** Working side			Balancing side			**Bilateral Incisor Bite**		
	Fx	Fy	Fz	Fx	Fy	Fz	Fx	Fy	Fz
Superficial masseter	−28.4	−57.4	121.3	23.6	−47.9	101.1	−15.8	−31.9	67.4
Deep masseter	−32.1	21.0	44.5	26.7	17.5	37.1	−11.6	7.6	16.1
Medial pterygoid	71.4	−54.6	116.1	−51.0	−39.0	83.0	66.3	−50.7	107.8
Anterior temporal	−17.2	−5.1	114.0	13.7	−4.0	90.5	−1.9	−0.6	12.5
Middle temporal	−13.9	31.5	52.8	14.2	32.0	53.6	−1.3	2.9	4.8
Posterior temporal	−9.3	38.1	21.1	6.1	25.2	14.0	−0.6	2.6	1.4
Lateral pterygoid	12.6	−15.2	−3.5	−27.4	−32.9	−7.6	29.9	−36.0	−8.3

Table 1 – Masticatory muscle forces. Force values reported in Unilateral Molar Bite refer to RMOL bite. In LMOL case, working side force values are applied to left side and vice versa on balancing side, and force vector x changes direction. In Bilateral Incisor Bite the applied muscular forces are the same for both sides, only force vector x is reversed.

Results

This study aims to evaluate the influence of lateral pterygoid muscle on TMJ biomechanical behaviour and to predict the effect of lateral pterygoid muscle detachment in the event of TMJ replacement. Thus, distribution of equivalent (Von–Mises) stress on both condyles and pattern of minimum principal elastic strain along a control line on mandibular bone (Fig. 1b) are collected with FEA.

Equivalent Von–Mises Stress

As shown in Table 2, the results of stress distribution in case of bilateral INC bite show that maximum occurs near to fixed support on incisors.

	Equivalent (Von-Mises) Stress (MPa)								
	INC			RMOL			LMOL		
	Total	Right	Left	Total	Right	Left	Total	Right	Left
Case A	16.2	12.8	13.0	34.5	13.7	34.5	33.3	32.3	13.1
Case B	15.5	15.0	13.9	35.3	14.9	35.3	35.3	34.3	13.3
Case C	20.0	14.6	13.3	34.5	15.0	34.5	35.2	34.3	12.9
Case D	20.2	13.1	13.6	35.3	13.6	35.3	33.3	32.3	13.5

Table 2 – Equivalent Von Mises Stress.

In Case A, when all muscle are acting, stress distribution is almost symmetric with a slight overload 1.7% on left side. On contrary, Case B shows a greater overload on right side of 7.3%. When only one lateral pterygoid is working (Case C and D) stress overload is registered on non–operating side, ie on balancing side. This result is reinforced in cases of unilateral bite. As shown in case RMOL and LMOL, the overloaded side is the balancing side. In natural condition (Case A–RMOL, LMOL), stress on balancing side is about 2.5 times working side. The stress overload in Case D–RMOL and in Case C–LMOL is the largest recorded with a difference between working and balancing side of about 2.6 times on balancing side and the minor difference of 2.3 times is collected in cases C–RMOL and D–LMOL. Maximum equivalent Von Mises stress are located on condylar neck and reach values of 35.3 MPa on balancing side for RMOL case and of 34.3 MPa on balancing side for LMOL case.

Minimum principal elastic strain

Minimum principal elastic strain informs about distribution of compressive strain along the mandibular bone. Strain distribution in INC case (Fig. 2) shows that on right side Case A and D follow the same pattern as well as Case B and C, and on left side this relation is reversed. In RMOL bite (Fig. 3), strain distribution on working side are nearly the same in all cases, but on balancing side Case A–C and Case B–D follow the same distribution. This trend is not so clear in LMOL simulation result (Fig. 4), because differences between cases are smaller. Minimum strain peaks on balancing side are detected on condyle neck and mandibular angle. On mandibular angle strain peak is −1.18e−3 mm/mm in case A,C–RMOL and −1.24e−3 mm/mm in Case B,D–RMOL, and −1.04e−3 mm/mm in Case A,D–LMOL and −1.09e−3 mm/mm in Case B,C–LMOL. During INC bite, maximum strain reaches almost half of unilateral molar bite cases.

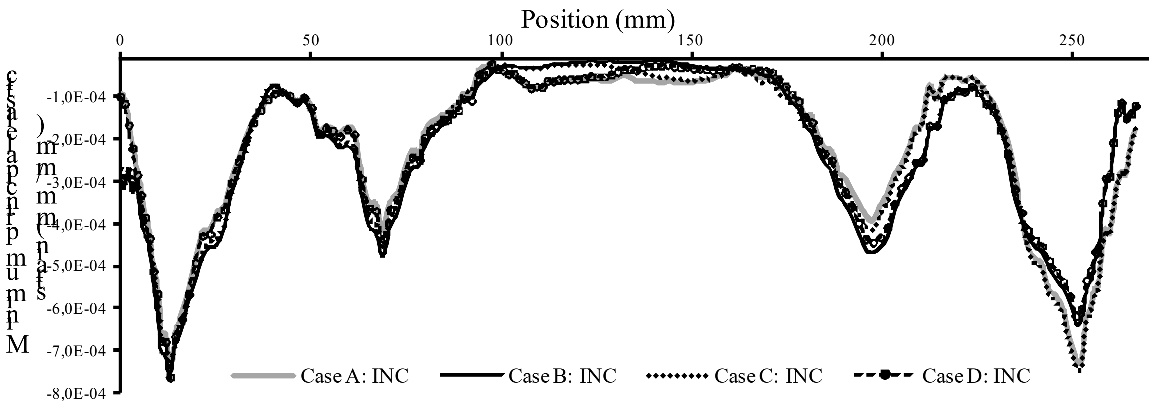

Figure 2 – Minimum principal elastic strain recorded on control line (from right to left condyle) of INC bite simulation.

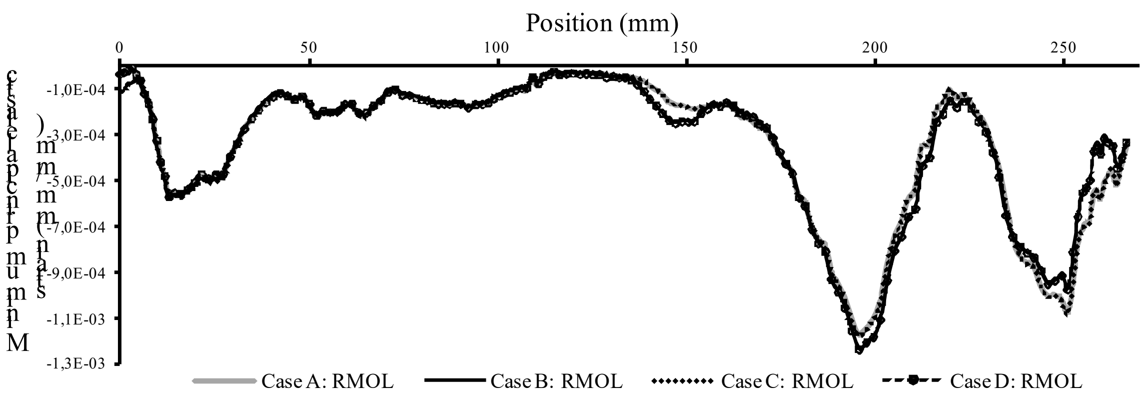

Figure 3 – Minimum principal elastic strain recorded on control line (from right to left condyle) of RMOL bite simulation.

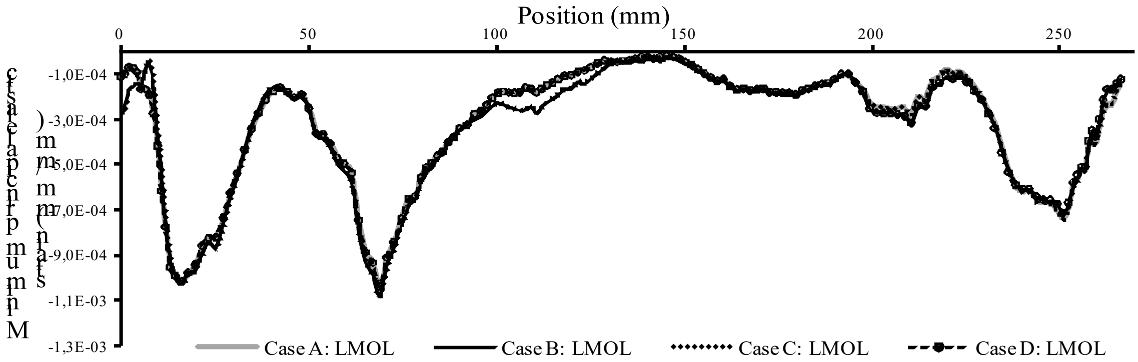

Figure 4 – Minimum principal elastic strain recorded on control line (from right to left condyle) of LMOL bite simulation.

Discussion

This FEA analysis performs bilateral (INC) and unilateral loading (RMOL, LMOL) bite and tests the influence of lateral pterygoid muscle on stress and compressive strain distribution. Case A simulates natural condition of bite with all masticatory muscles in action, Case B considers a total lack of lateral pterygoid muscle and Case D and C tests the influence of the left and right muscle, respectively, during the three loading bites. Stress and strain results in case of unilateral bite show that TMJ maximum functional loading occurs during molar biting [16]. During unilateral bite, maximum stress on mandibular bone increases on balancing side, or contralateral side of bite. This result coincides with several studies found in the literature [8,10,17]. The influence of lateral pterygoid muscle on working side is observed in Case D–RMOL and in Case C–LMOL, when only lateral pterygoid on working side is acting. The similarity between natural case and D–RMOL and C–LMOL informs that muscle on working side could be considered the responsible of contralateral overloading. Hylander study of TMJ mechanics (17)and in particular the human mandible, is generally thought to function as a lever during biting. This notion, however, has not gone unchallenged. Various workers have suggested that the mandible does not function as a lever, and they base this proposition on essentially two assertions: (1 found that during molar bite muscles on working side seem to be more active and so to keep TMJ system in static equilibrium reaction forces on balancing side are larger than working side. Moreover, in literature [8] balancing side is called also resting side, so that the similarity between stress and strain distribution of Case B and C in RMOL bite, and Case B and D in LMOL bite are explained. Kumazaki´s clinical study of patients with unilateral disc displacement [18] observed that patients with this TMJ disorder on one side, prefer to use the unhealthy side as the working side, because it generates less pain.

Comparing results of this study with previous ones [19,20] which simulates bilateral and unilateral bite on unilateral TMJ replacement system neglecting lateral pterygoid muscle, was noticed that contralateral overloading also occurred. Moreover, the case of TMJ prosthesis implanted on balancing side is observed to be the worst in terms of maximum stress calculated on prosthesis, it reaches almost 2.8 times the value of bilateral bite. The same trend was observed by Van Loon *et al*. [21] in a three–dimensional mathematical study.

Conclusion

In conclusion, FEA analysis performed in this study obtained result of TMJ biomechanical behaviour in agreement with data found in literature. The unilateral bite is the more critical loading because it creates a load difference between the two sides increasing loading on balancing side. This overloading increases if only lateral pterygoid muscle on working side is active. Thus, it could be predicted that TMJ replacement implanted on balancing side suffers a greater loading. However, with data collected in this study it is not possible to clearly analyze the influence of lateral pterygoid on TMJ replacement implanted on working or balancing side. As future perspectives, it should be performed a FEA simulating bilateral and unilateral bite on TMJ with implanted replacement device and the action of lateral pterygoid muscle on working and balancing side.

Acknowledgments

The authors wish to acknowledge the financial support provided by the Scientific Research Foundation for the State of São Paulo (FAPESP – grant 2015/20630–4) and National Council for Scientific and Technological Development (CNPq – Process 573661/2008–1), and by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES – Finance Code 001).

References

[1] Bayat M, Abbasi AJ, Noorbala AA, Mohebbi SZ, Moharrami M, Yekaninejad MS. Oral health–related quality of life in patients with temporomandibular disorders: A case–control study considering psychological aspects. Int J Dent Hyg [Internet]. 2018;**16(1)**:165–70. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/idh.12266

[2} Lotesto A, Miloro M, Mercuri LG, Sukotjo C. Status of alloplastic total temporomandibular joint replacement procedures performed by members of the American Society of Temporomandibular Joint Surgeons. Int J Oral Maxillofac Surg [Internet]. 2017;**46(1)**:93–6. Available from: http://www.sciencedirect.com/science/article/pii/S090150271630176X

[3] De Meurechy N, Mommaerts MY. Alloplastic temporomandibular joint replacement systems: a systematic review of their history. Int J Oral Maxillofac Surg. 2018;**47(6)**:743–54.

[4] Zou L, He D, Ellis E. A Comparison of Clinical Follow–Up of Different Total Temporomandibular Joint Replacement Prostheses: A Systematic Review and Meta–Analysis. J Oral Maxillofac Surg [Internet]. 2018;**76(2)**:294–303. Available from: http://www.sciencedirect.com/science/article/

pii/S027823911731145X

[5] Linsen SS, Reich RH, Teschke M. Mandibular Kinematics in Patients With Alloplastic Total Temporomandibular Joint Replacement—A Prospective Study. J Oral Maxillofac Surg [Internet]. 2012;**70(9)**:2057–64. Available from: http://www.sciencedirect.com/science/article/pii/S0278239112006738

[6] Briceño F, Ayala R, Delgado K, Piñango S. Evaluation of temporomandibular joint total replacement with alloplastic prosthesis: observational study of 27 patients. Craniomaxillofac Trauma Reconstr [Internet]. 2013/06/04. 2013;**6(3)**:171–8. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24436755

[7] Leandro LF, Ono HY, Loureiro CC, Marinho K, Guevara HA. A ten-year experience and follow-up of three hundred patients fitted with the Biomet/Lorenz Microfixation TMJ replacement system. Int J Oral Maxillofac Surg. 2013/06/19. 2013;**42(8)**:1007–13.

[8] Hylander W. Functional Anatomy of the TMJ. 2006.

[9] Kerwell S, Alfaro M, Pourzal R, Lundberg HJ, Liao Y, Sukotjo C, et al. Examination of failed retrieved temporomandibular joint (TMJ) implants. Acta Biomater. 2016/01/16. 2016;**32**:324–35.

[10] Lundberg HJ. TMJ Biomechanics. In: Temporomandibular Joint Total Joint Replacement – TMJ TJR: A Comprehensive Reference for Researchers, Materials Scientists, and Surgeons [Internet]. Cham: Springer International Publishing; 2016. p. 3–28. Available from: https://doi.org/10.1007/978-3-319-21389-7_1

[11] Rodrigues YL, Mathew MT, Mercuri LG, da Silva JSP, Henriques B, Souza JCM. Biomechanical simulation of temporomandibular joint replacement (TMJR) devices: a scoping review of the finite element method. Int J Oral Maxillofac Surg. 2018/03/13. 2018;**47(8)**:1032–42.

[12] Carter DR, Spengler DM. Mechanical properties and composition of cortical bone. Clin Orthop Relat Res. 09/01. 1978;**(135)**:192–217.

[13] Hsu JT, Huang HL, Tsai MT, Fuh LJ, Tu MG. Effect of screw fixation on temporomandibular joint condylar prosthesis. J Oral Maxillofac Surg. 2011/01/11. 2011;**69(5)**:1320–8.

[14] Ramos A, Completo A, Relvas C, Mesnard M, Simoes JA. Straight, semi-anatomic and anatomic TMJ implants: the influence of condylar geometry and bone fixation screws. J Craniomaxillofac Surg. 08/31. 2010;**39(5)**:343–50.

[15] Korioth TW, Hannam AG. Deformation of the human mandible during simulated tooth clenching. J Dent Res. 1994/01/01. 1994;**73(1)**:56–66.

[16] Mercuri LG, Edibam NR, Giobbie-Hurder A. Fourteen-year follow-up of a patient-fitted total temporomandibular joint reconstruction system. J Oral Maxillofac Surg. 05/23. 2007;**65(6)**:1140–8.

[17] Hylander WL. The human mandible: lever or link? Am J Phys Anthr. 09/01. 1975;**43(2)**:227–42.

[18] Kumazaki Y, Kawakami S, Hirata A, Oki K, Minagi S. Ipsilateral Molar Clenching Induces Less Pain and Discomfort than Contralateral Molar Clenching in Patients with Unilateral Anterior Disc Displacement of the Temporomandibular Joint. J Oral Facial Pain Headache. 2016/07/30. 2016;**30(3)**:241–8.

[19] Mazzocco AG, Jardini AL, Nunes EL, Filho RM. Custom-made temporomandibular joint prosthesis: Computer aided modeling and finite elements analysis. Vol. 74. Chemical Engineering Transactions; 2019. p. 1489–94.

[20] Huang HL, Su KC, Fuh LJ, Chen MY, Wu J, Tsai MT, et al. Biomechanical analysis of a temporomandibular joint condylar prosthesis during various clenching tasks. J Craniomaxillofac Surg. 2015/06/02. 2015;**43(7)**:1194–201.

[21] Van Loon JP, Otten E, Falkenstrom CH, de Bont LG, Verkerke GJ. Loading of a unilateral temporomandibular joint prosthesis: a three-dimensional mathematical study. J Dent Res. 11/21. 1998;**77(11)**:1939–47.