15th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering
and
3rd Conference on Imaging and Visualization
CMBBE 2018
P. R. Fernandes and J. M. Tavares (Editors)

FINITE ELEMENTS ANALYSIS OF THE STRESS DISTRIBUTION ON TEMPOROMANDIBULAR JOINT DUE TO THE USE OF MANDIBULAR ADVANCEMENT DEVICES

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Keywords: Temporomandibular Joint, Temporomandibular Ligaments, Articular Disc, Mandibular Advancement Device, Obstructive Sleep Apnoea Syndrome, Finite Elements Model.

Abstract: *Mandibular Advancement Devices (MADs) are therapeutic tools frequently used for the treatment of Obstructive Sleep Apnoea Syndrome (OSAS). Patients suffering from OSAS show repeated phenomena of oropharynx obstruction during sleep, which alter the airway volume and the breathing airflow. By advancing the mandible, MAD increases the airway volume and allows the patient to breathe better and consequently to sleep better. However, the use of MAD, forcing the mandible forward, causes the development of not negligible stresses on temporomandibular joint (TMJ).*

The main goal of this study is to analyse the stress distribution on temporomandibular joint by means of finite elements simulations.

The 3D reconstruction of TMJ begins with the extraction of anatomical 3D models from the CT images of the patient's skull. The 3D meshes of the mandible and temporal bones are then smoothed, defeatured and transformed in NURBS surface models by mean of reverse engineering techniques. Soft tissues (articular disc and ligaments), which cannot be identified from CT images, are modelled according to anatomical atlas and by using geometric reconstruction tools of specific CAD software.

The roto-translation of the mandible, due to the use of MAD, is experimentally determined from the scans of the moulds of dental arches (closed mouth) with and without MAD.

The mechanical properties for each component of the mandibular system are derived from previous studies. Simulations are conducted by imposing two different displacements (by advancing the lower plate of MAD) and without imposing external loads.

Preliminary results show the qualitative stress distribution on condyle, ligaments and articular disc. Quantitative results are comparable to those obtained in literature with simulations of non-pathological normal joint. The proposed simulation model will allow to compare the stress distribution on soft and hard tissues, due to the use of different MAD. For this reason, future work will include the design of MAD and periodontal ligament, in order to *study the tensile state of the anatomical parts, on the basis of different MAD's materials and fulcrum positioning.*

1 INTRODUCTION

Obstructive Sleep Apnoea Syndrome (OSAS) consists in recurrent partial or total obstruction episodes in the airways during the sleep, characterized by apnoea and hypopnoea [1]. The severity of OSAS is estimated through the apnoea-hypopnoea index (AHI) that considers the total number of apnoea (complete airways obstructions) and hypopnoea (partial breathing obstructions) per hour of sleep. OSAS is diagnosed when the AHI is higher than 15 without any other associated symptom, and when AHI > 5 with daytime sleepiness and other symptoms.

Although nowadays the gold standard treatment for OSAS is the C-PAP method (Continuous Positive Airway Pressure) [2, 3], Mandibular Advancement Devices (MADs) are increasingly used by patients with a mild or moderate syndrome [4, 5]. Several kind of MADs are commercially available. These ones differ in materials, shape and fulcrum placement but all of them produce the same effect on the upper airways: the increment of the airways volume (and thus that of the airflow) through the mandibular advancement [6].

Nevertheless, by advancing the mandible, each device produces not negligible stress on the temporomandibular joint (TMJ) and, consequently, some patients report soreness or pain in the TMJs or jaw muscles during orthodontic treatment, especially at the awakening.

For this reason, although the use of MADs in OSAS patients is encouraged by last literature review on oral device [7], their effects on TMJ deserve a more in-depth investigation since their use is not limited to short periods but often it is a lifelong therapy.

Moreover, the anterior and inferior mandibular reposition during treatment can leads small adaptive changes inducing condylar remodelling. For this reason, in case of use of MAD, the load distribution on condyle and articular disc has a great importance.

The objective of this paper is the assessment of the stress distribution on TMJ in case of MAD usage, through the Finite Element Method (FEM). The simulation model presented in this paper includes jawbone, glenoid fossa (i.e. temporal bone), articular disc and TMJ ligaments (temporomandibular, sphenomandibular and stylomandibular). In future works, authors will model also dental arches, periodontal ligaments and mandibular advancement devices.

Several authors proposed finite elements models of TMJ in order to study the physiological stress/strain behaviour of the masticatory system under normal occlusal loads [8, 9] and during mandibular lateral excursions [10] or protrusion [11, 12]. Some papers evaluated also the effect of abnormal loading, such as awake and asleep bruxism [13] or prolonged clenching [14], but the effects of MADs have not be still investigated.

The TMJ virtual prototype proposed in this paper is the start point for exploring the effects of different MADs on such joint.

2 MATERIALS AND METHODS

2.1 Anatomical 3D reconstruction

The anatomical 3D reconstruction of TMJ begins with the extraction of 3D models of bones from computed tomography images of the patient's skull [15, 12], as shown in Fig.1.

Thanks to the symmetry of the skull across the sagittal plane, it is suitable to reconstruct only half cranium consisting in one condyle, half mandible and one partial temporal bone with the glenoid fossa, in order to lighten and simplify the simulation model.

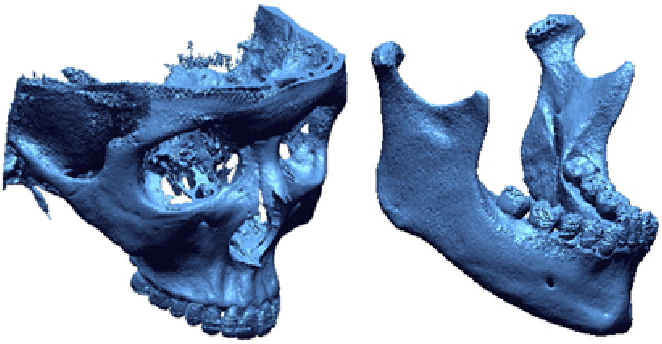
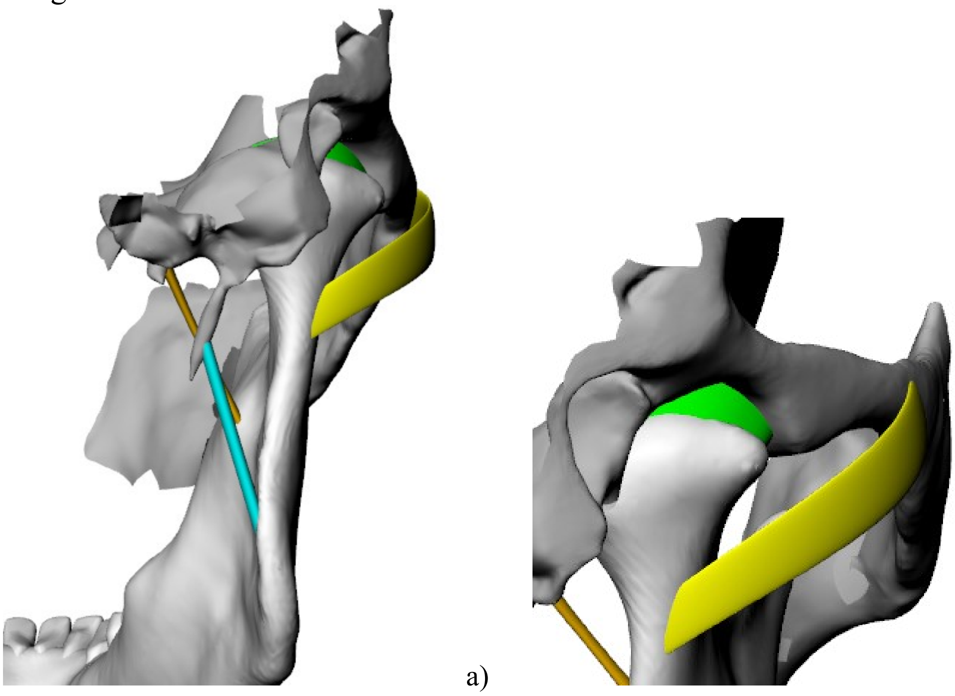


Fig.1: 3D models of skull and mandible, extracted from CT images

In order to repair defects and irregularities, the meshes of half mandible (with condyle) and temporal bone (with glenoid fossa) are smoothed, defeatured and transformed in NURBS surface models by means of reverse engineering techniques.
Articular disc and TMJ ligaments cannot be reconstructed from CT images because computed tomography does not allow the visualization of soft tissues. For this reason, the reconstructed surfaces of mandible and temporal bone are imported in a 3D CAD software, where soft elements have been modelled based on anatomical atlas. The 3D model of TMJ is shown in Fig.2.



a) b)

Fig.2: a) posterior view of TMJ 3D model and (b) condyle detail. Articular disc (green) and temporomandibular (yellow), sphenomandibular (gold), stylomandibular (cyan) ligaments.

The articular disc has been designed by extracting the upper surface of the condyle toward

the glenoid fossa, as in [16].
Regarding the modelling of ligaments, this paper presents a step forward compared to the literature. Indeed in [16], ligaments are introduced as virtual linear springs and in [10, 13] only collaterals and temporomandibular ligaments have been modelled. In this work, in order to improve the model accuracy, all the three main TMJ ligaments have been considered, because sphenomandibular and stylomandibular ligaments have an important biomechanical role on mandible opening [17].
Therefore temporomandibular, sphenomandibular and stylomandibular ligaments have been modelled through 3D reconstruction tools according to anatomical drawings and medical literature. Ligaments length, origin and insertion points have been identified as explained in [18], where angles of inclination between the principal axis of the ligaments and the inner surface of the mandible are illustrated.

2.2 Determination of mandibular displacement

The roto-translation of the mandible wearing a MAD is specific of each device because it depends on the MAD mechanism. The mandible displacement caused by a specific MAD has been experimentally determined from the scans of the moulds of dental arches with and without MAD. Firstly, the two moulds of dental arches have been scanned in rest condition (closed mouth, Fig.3a) and then, assembled with the upper and lower plates of the MAD, they have been scanned again (Fig.3b). In this second 3D acquisition, the advancement imposed by the lower plate of MAD to mandible was equal to 2 mm. By overlapping the two scans (a and b) and by matching the upper, maxillary parts it is possible to calculate the roto-translation of the mandible imposed by MAD (Fig.3c).

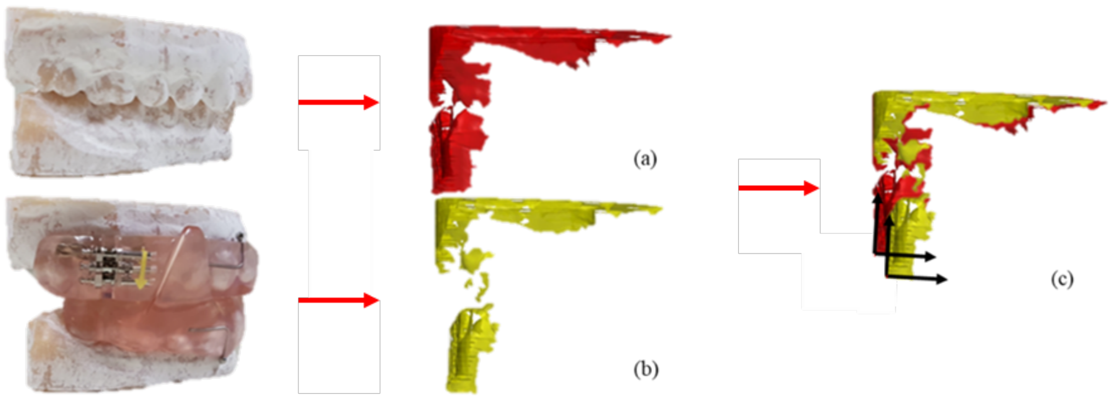


Fig.3: a) Scan of the teeth moulds in rest position; b) Scan of the teeth moulds with MAD; c) Scans overlapping for determining mandible roto-translation.

The same procedure has been followed to calculate the roto-translation of the mandible with a further advancement of the MAD lower plate of 3 mm, thus forcing the mandible 5 mm forward.

2.3 Analysis Setup

Starting from the 3D TMJ model previously defined, a Finite Element virtual prototype has been realised in *Ansys Workbench 15.0*. The development of a simplified simulation model

(half cranium without teeth) allows to importantly decreasing the computing effort.
The materials models used for simulating the anatomical components of the mandibular system are isotropic, linear, elastic [11, 12, 17, 19] and the mechanical properties for each component, listed in Table 1, have been derived from previous studies [11].

Table 1: Mechanical properties of anatomical components

	Elastic Modulus (E), MPa	Poisson’s Ratio (v)
Mandible (Compact bone)	**13˙700.00**	**0.30**
Glenoid Fossa (Compact bone)	**13˙700.00**	**0.30**
Articular disc	**10.00**	**0.40**
Stylomandibular ligament	**0.49**	**0.49**
Sphenomandibular ligament	**0.49**	**0.49**
Temporomandibular ligament	**0.49**	**0.49**

The boundary conditions have been defined as follows:
- Fixed: ground to temporal bone
- Bonded: condyle to articular disc
- Frictionless: articular disc to glenoid fossa
- Bonded: temporomandibular ligament to temporal bone
- Bonded: temporomandibular ligament to mandible
- Bonded: sphenomandibular ligament to temporal bone
- Bonded: sphenomandibular ligament to mandible
- Bonded: stylomandibular ligament to temporal bone
- Bonded: stylomandibular ligament to mandible

The temporal bone has been fixed in order to avoid rigid movement of the anatomical parts. ‘Bonded’ contact does not allow relative motion (nor sliding nor separation) between the surfaces involved, while ‘frictionless’ contact allows separation and sliding of the surfaces involved. Therefore, the ‘bounded’ contact between condyle and articular disc is necessary for avoiding ‘rigid body motion’ errors during the simulation, while, thanks to the ‘frictionless’ contact, the disc is free to slide on the glenoid fossa and separate from it.
The mesh has been developed using tetrahedral elements because this type of element best suits freeform surfaces as bones and ligaments. The simulation model consists of about 20˙000 elements (Fig.4).
Simulations have been conducted without imposing external loads. The tensile state derives from the two different roto-translations previously calculated and imposed to the mandible.

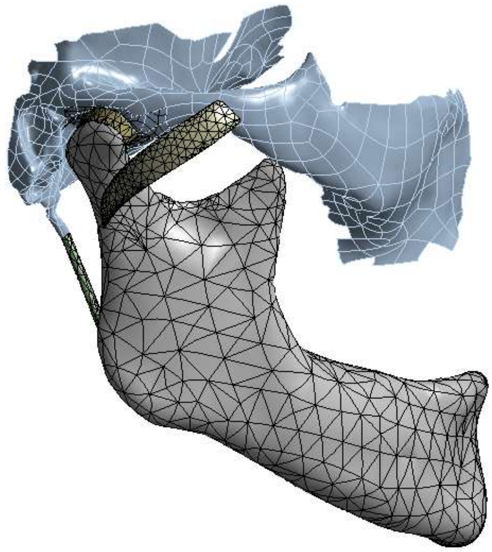


Fig.4: Tetrahedral mesh of the model

3 RESULTS AND DISCUSSION

This section presents the preliminary results related to the stress distribution on condyle, articular disc and ligaments (Fig.5, Fig.6 and Fig.7). Quantitative results of load analysis are comparable to those obtained in literature with simulations of non-pathological normal joint in standard occlusion.

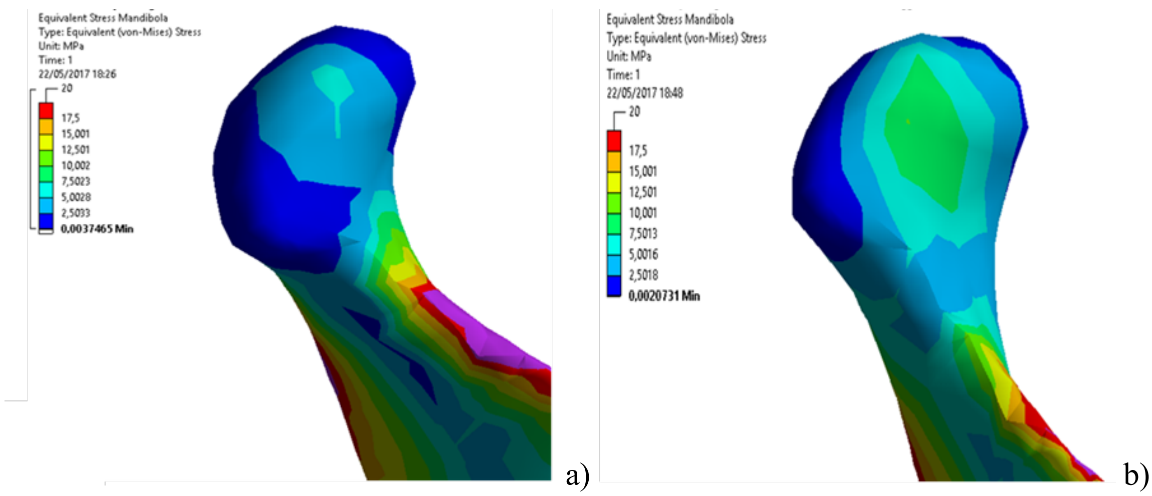


Fig.5: Von-Mises stress on mandible condyle with a MAD lower plate advancement of 2 mm (a) and 5 mm (b)

As shown in Fig.5, the pick stress value on the condyle for a mandibular advancement of 2 mm is about 5MPa; this value raise until about 10Mpa for an advancement of 5 mm, involving a wider area. These results are comparable with those found by Citarella et al. in

[8] where stress distribution was evaluated simulating a standard loading action performed by the masticatory muscles in centric occlusion.

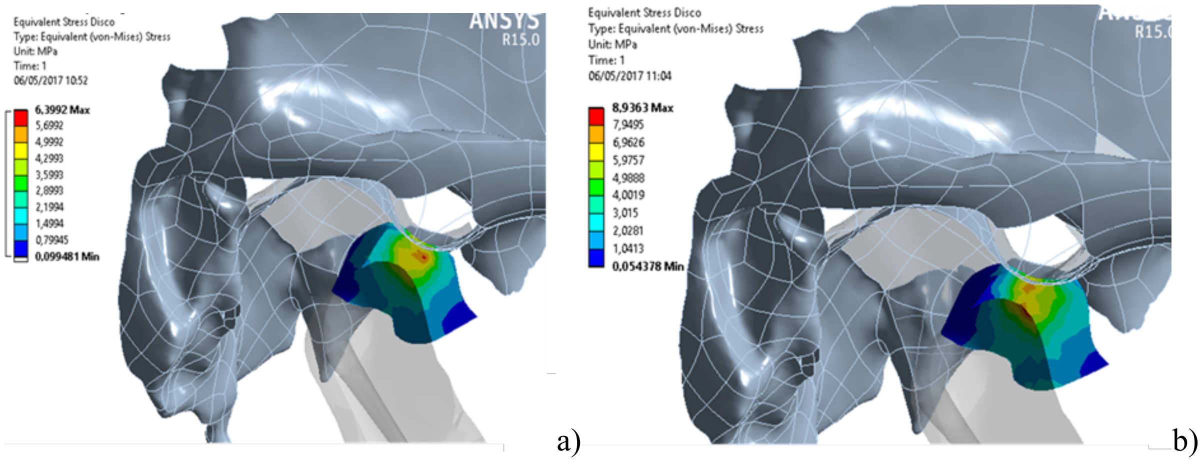


Fig.6: Von-Mises stress on articular disc (transversal section) with a MAD lower plate advancement of 2 mm (a) and 5 mm (b)

The tensile state of the articular disc is comparable with those one found by Shrivastava in [12]. Fig.6 highlights that, in both cases, the roto-translation of the mandible causes a maximum stress on the central area of the disc, confirming its role in spreading functional load and preventing articular disease.
Different authors investigated the load that articular disc, formed for the 80% of type I collagen fibres, can stand for its mechanical characteristics. Resistance values of the type I collagen fibres of the disc present a resistance to deformation ranging between 20-35MPa and 50MPa for the tension [20, 21]. These values are significantly higher than maximum Von-Mises stress obtained in this study (equal to 6,4Mpa in the first case and to 8,9Mpa in the second case). Therefore, slight mandibular advancement can be considered a safe procedure even for the long period.

Lastly, Fig.7 shows the tensile state of TMJ ligaments: the temporomandibular one is the less stressed. The stylomandibular ligament is mainly stressed close to its connection with the mandible, while the pick stress value of the sphenomandibular ligament is located in the middle of its length, where the section is smaller.

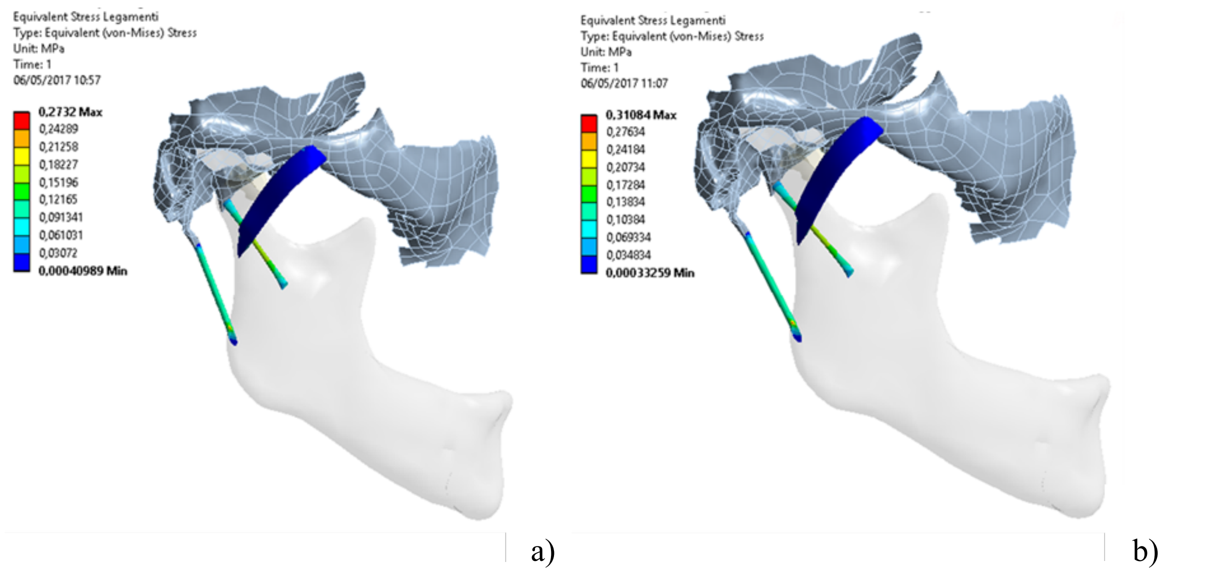


Fig.7: Von-Mises stress on temporomandibular, sphenomandibular and stylomandibular ligaments with a MAD lower plate advancement of 2 mm (a) and 5 mm (b)

4 CONCLUSIONS

This study demonstrates that, although deformation and load values induced by MAD increase with the mandibular advancement, these are lower than physiological limits of the anatomical parts evaluated. Therefore, slight mandibular advancement can be considered a safe procedure even for the long period and should not cause permanent side effects.
Respect to other works in literature, the model proposed in this paper will allow to precisely comparing the movement imposed by different MADs, and thus the consequent stress distribution on soft and hard tissues.
In order to overcome the limitations of the presented simulation model, future works will regard:

- The shape of the disc: it should be extended in its surface, for more enveloping the condyle and reducing computational problems during the simulation;
- The material model: it should be more complex, such as nonlinear and anisotropic models;
- The boundary conditions: contact models must be improved according to limitations.

Moreover, future work will include also the design of teeth, periodontal ligaments and MAD, in order to study the tensile state of the anatomical parts, due to different MAD's materials and fulcrum positioning. By analysing such results and combining them with clinical analyses, clinicians can extract useful rules for prescribing the best fitting MAD according to the severity of OSAS.

REFERENCES

[1] E. Azagra-Calero, E. Espinar-Escalona, J.M. Barrere-Mora, J.M. Llamas-Carreras, E. Solano-Reina. Obstructive sleep apnea syndrome (OSAS). Review of the literature. *Medicina Oral, Patologia Oral y Cirugia Bucal,*17(6), e925-929, 2012.

[2] J.M. Marin, S.J. Carrizo, E. Vicente, A.G. Agusti. Long-term cardiovascular outcomes in men with obstructive sleep apnoea-hypopnoea with or without treatment with continuous positive airway pressure: An observational study. *Lancet* 365, 1046-53, 2005.

[3] S. Tregear, J. Reston, K. Schoelles, B. Phillips. Continuous positive airway pressure reduces risk of motor vehicle crash among drivers with obstructive sleep apnea: systematic review and meta-analysis. *Sleep*, 33(10), 1373-1380, 2010.

[4] S. Serra-Torres, C. Bellot-Arcís, J.M. Montiel-Company, J. Marco-Algarra, J.M. Almerich-Silla. Effectiveness of mandibular advancement appliances in treating obstructive sleep apnea syndrome: A systematic review. *Laryngoscope*, 126(2), 507-14, 2016.

[5] T.E. Weaver, R.R. Grunstein. Adherence to continuous positive airway pressure therapy: the challenge to effective treatment. *Proceedings of the American Thoracic Society*, 15, 5(2), 173-178, 2008.

[6] A.S. Chan, K. Sutherland, R.J. Schwab, B. Zeng, P. Petocz, R.W. Lee, M.A. Darendeliler, P.A. Cistulli. The effect of mandibular advancement on upper airway structure in obstructive sleep apnoea. *Thorax*, 65(8), 726-732, 2010.

[7] K. Ramar, L.C. Dort, S.G. Katz, C.J. Lettieri, C.G. Harrod, S.M. Thomas, R.D. Chervin. Clinical Practice Guideline for the Treatment of Obstructive Sleep Apnea and Snoring with Oral Appliance Therapy: An Update for 2015. *Journal of Clinical Sleep Medicine*, 11(7), 773-827, 2015.

[8] R. Citarella, E. Armetani, F. Caputo, A. Naddeo. FEM and BEM Analysis of a Human Mandible with Added Temporomandibular Joints. *The Open Mechanical Engineering Journal*, 6, 100-114, 2012.

[9] M. Fricová, Z. Horák, S. Konvicková, R. Jirman. Modelling Of Temporomandibular Joint And FEM Analysis. *Acta Of Bioengineering And Biomechanics*, 8 (1), 2006.

[10] A. Pérez del Palomar, M. Doblaré. Finite element analysis of the temporomandibular joint during lateral excursions of the mandible. *Journal of Biomechanics* 39, 2153–2163, 2006.

[11] A. Gupta, V.S. Kohli, P.V. Hazarey, O.P. Kharbanda, A. Gunjal. Stress distribution in the temporomandibular joint after mandibular protraction: A 3-dimensional finite element method study. *American Journal of Orthodontics and Dentofacial Orthopedics* 135, 737-756, 2009.

[12] A. Shrivastava, P.V. Hazarey, O.P. Kharbanda, A. Gupta. Stress distribution in the temporomandibular joint after mandibular protraction: A three-dimensional finite element study. *Angle Orthodontist* 85,196–205, 2015.

[13] M.S. Commisso, J. Martìnez-Reina, J. Mayo. A study of the temporomandibular joint during bruxism. *International Journal of Oral Science* 6, 116–123, 2014.

[14] C. Nishio, K. Tanimoto, M. Hirose, S. Horiuchi, S. Kuroda, K. Tanne, E. Tanaka. Stress analysis in the mandibular condyle during prolonged clenching: a theoretical approach with the finite element method. *Proceedings of IMechE Vol. 223 Part H: Journal of Engineering in Medicine*, 739-748, 2009.

[15] W. Mingyi, Q. Xingzhou, C. Min, W. Dongmei, Z. Chenping. Biomechanical three-dimensional finite element analysis of prostheses retained with/without zygoma implants in maxillectomy patients. *Journal of Biomechanics* 46, 1155–1161, 2013.

[16] Y.M. Alkhiary, T.M. Nassef, I.A. Yassine, S.B. Tayel, A.E. Ezzat. A New Numerical Model to Analyze Stress Distribution of TMJ Disc from 2-D MRI Scans. *Advances in Computing*, 2(5), 66-75, 2012.

[17] C. Savoldelli, P.O. Bouchard, R. Loudad, P. Baque, Y. Tillier. Stress distribution in the temporo-mandibular joint discs during jaw closing: a high-resolution three-dimensional finite-element model analysis. *Surgical and Radiologic Anatomy* 34, 405–413, 2012.

[18] A.M. Cuccia, C. Caradonna, D. Caradonna. Manual Therapy of the Mandibular Accessory Ligaments for the Management of Temporomandibular Joint Disorders. *The Journal of the American Osteopathic Association* 111(2), 102-112, 2011.

[19] M. Beek, J.H. Koolstra, L.J. Ruijven, T.M.J. Eijden. Three-dimensional finite element analysis of the human temporomandibular joint disc. *Journal of Biomechanics,* 33(3), 307-316, 2000.

[20] C. Kober, R. Sader, H. Thiele, H.J. Bauer, H.F. Zeilhofer, K.H. Hoffmann, H.H. Horch. Numerical simulation (FEM) of the human mandible: validation of the function of the masticatory muscles. *Biomedical Technology*, 45(7-8), 199-205, 2000.

[21] A. Shimazaki, H. Kimura, N. Inou, K. Maki. Development of a measurement system for the mechanical load of functional appliances. *Journal of Biomechanics*, (17), 30434-30437, 2017.