Int. J. Advanced Design and Manufacturing Technology, 2025, Vol. 18, No. 3, pp. 11-16

DOI: *ISSN: 2252-0406* *https://admt.isfahan.iau.ir*

Estimation of Crack Propagation in Edentulous Mandibular Bone using Finite Element Analysis

Tayebeh Tazh, Kamran Hassani *, Siamak Khorramymehr
Department of Biomedical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
E-mail: Tayebeh.tazh513@gmail.com, k.hasani@srbiau.ac.ir, s.khorramymehr@srbiau.ac.ir
*Corresponding author

Mohammad Nikkhoo
School of Physical Therapy and Graduate Institute of Rehabilitation Science, College of Medicine, Chang Gung University, Taoyuan, Taiwan
E-mail: d000018523@cgu.edu.tw

Received: 3 May 2025, Revised: 21 June 2025, Accepted: 24 September 2025

Abstract: Mandibular fractures can lead to serious problems such as mandibular deficiency, deviation and asymmetry in patients. Finite element analysis is employed for evaluating the amount and location of cracks in the mandibular bone. In this context, the jawbone thickness impact on maximum stress and crack location in a real human jaw geometry with heterogeneous bone properties and under chewing loading has not been investigated. Here, the mandibular bone thickness impact on the creation and propagation of cracks has been investigated using finite element analysis using ABAQUS software. The studied geometry was created using the 3D scanning technology of a resorbed edentulous jaw. The place of crack is not predetermined, and its starting point is assumed to be at the point of maximum stress. The properties of bones are considered viscoelastic and heterogeneous. Findings reveal that the maximum von Mises stress decreases with increasing jawbone thickness. Also, by increasing the bone thickness, the rate of crack propagation decreases, so that no cracks are formed in the mandibular bone when the thickness is greater than 10.8 mm. In fact, if the thickness of the mandibular bone in people with an atrophic edentulous mandible is less than 10.8 mm, the possibility of failure due to muscle forces and their combination with the chewing forces of the person will be possible.

Keywords: Crack Propagation, 3D Scanning, Finite Element Analysis, Mandibular Bones, Viscoelastic

Biographical notes: Tayebeh Tazh is currently a PhD student of Biomechanics in the Science and Research Branch of Islamic Azad University. **Kamran Hassani** is an associate professor at the Science and Research Branch of Islamic Azad University. **Siamak Khorramymehr** is an Assistant Professor in the Science and Research Branch of Islamic Azad University. **Mohammad Nikkhoo** is an Assistant Professor in Medical Sciences and Technologies at the Science and Research Branch of Islamic Azad University.

Research paper

1 INTRODUCTION

One of the most common jaw fractures is a mandibular fracture. A jaw fracture can cause difficulty in eating and speaking, and if left untreated, may lead to facial deformity and asymmetry. There are various methods for diagnosing, classifying, and treating mandibular fractures. The mandible fractures hinder the craniofacial skeleton development in growing individuals, resulting in ankylosis, asymmetry, or mandibular insufficiency [1-2]. The mandibular bone includes the ramus and body regions. In the body region, fractures of the parasymphysis and symphysis are very common. The treatment of a fracture, whether open or closed, is dependent upon the fracture type, the surgeon's expertise, the patient's medical conditions, and the accessible facilities, with each technique presenting distinct challenges and difficulties [3].

Experimental or numerical simulation methodologies may be implemented to evaluate the biomechanics of fractures in the mandible. Due to the clinical complexities involved in diagnosing the bone fracture process, fracture biomechanics are investigated using numerical modeling techniques, including finite element analysis [1-2]. By numerically simulating mandibular fractures and examining the distribution of stresses in different fracture areas, a precise comprehension of fracture biomechanics can be attained in order to develop appropriate treatment strategies [4-5]. In fact, this analysis enables the assessment of the position, dimensions, and strength of the bone system, which in turn facilitates the development of an optimal fracture treatment process. An effective numerical modeling method for evaluating the mandibular biomechanical behavior is finite element analysis (FEM) [6-8].

Volmer et al. [9] experimentally investigated the deformation of the mandible under mechanical loads and compared the results with the values obtained from finite element analysis. By comparing the numerical and experimental data, a good correlation was observed between the numerical modeling laboratory findings (correlation coefficient = 0.992). According to their findings, finite element analysis can be used as a non-invasive, valid, and accurate tool for predicting a variety of parameters related to the intricate biomechanical features of the mandible. Employing FEM, Kavanagh et al. [10] investigated the stress in various mandible regions for two samples of intact and fractured jawbones. Comparing their findings to experimental investigations, they demonstrated that numerical modeling can accurately predict the regions of the mandible that experience high stress. Therefore, the use of numerical modeling can help provide appropriate treatment strategies for fractured jaws. Hedesiu et al. [11] conducted a numerical analysis of the mandibular bone biomechanical features in the presence of bone trauma. They used a human jaw model with specified thickness and average properties for the jawbone. Their findings indicate that the edentulous jawbone undergoes a maximal stress of 1.3 MPa and a deformation of 1.6 mm when subjected to the applied impact force. This stress value results in the formation of fractures in the jawbone. Santos et al. [12] investigated the distribution of stress in a model of the edentulous mandible, having an effect of impact force caused by the injury, employing FEM. The properties of the jawbone were considered homogeneous in their work. They assessed the effect of the location and amount of the applied force on the amount and distribution of the maximum stress. Their results showed that applying impact force to the mandible creates maximal stress in the upper jaw and neck areas, which increases the likelihood of failure in these regions.

Prior research has shown the validity of the FEM in examining the quantity and location of fractures in the mandible bone. The impact of jawbone thickness on the distribution of maximal stress and the location of fractures in an actual human jaw geometry with heterogeneous bone properties under chewing loading has not been examined in previous studies. Here, FEM is employed to determine the propagation of cracks in a precise geometry of a resorbed edentulous mandible bone. The mandible geometry was created using 3D scanning technology of the human jaw, and the bone properties are considered heterogeneous. By measuring the jawbone thickness, the relationship between fracture and jawbone thickness under chewing force loading is investigated. In this regard, five CT scan samples of the mandible with different thicknesses are compared. Additionally, crack propagation in various samples is examined.

2 MATERIALS AND METHODS

2.1. Problem Description

A three-dimensional FEM of an edentulous, resorbed jawbone was done using ABAQUS 2018 software. The bone geometry was accurately modelled using computed tomography (CT) images of an individual jaw using Mimics software. Mimics is to create 3D models of medical images. These models can be used for engineering analyses and surgical simulations [11]. CT images were selected from five adults whose bone bodies ranged in thickness from 10.2 to 11 mm, with a variation of 2.0 mm between them. The longitudinal and transverse thickness of the body region of each model is given in “Table 1”. Also, “Fig. 1” shows the image of the model used along with its geometric specifications. As shown in “Table 1”, the thickness of the jawbone in the height of the body has decreased by 0.2 mm, while there have been minor changes in the width [13].

Table 1 The body region thickness in both the longitudinal and transverse directions for each case

Case	Body Height [mm]	Body Width [mm]
1	10.23	10.87
2	10.42	10.91
3	10.62	11.01
4	10.81	11.14
5	11.02	11.23

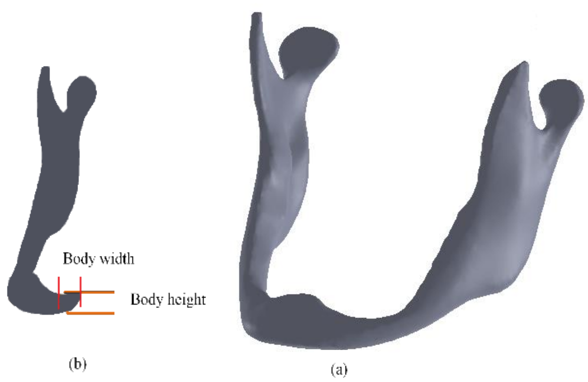

Fig. 1 (a): Image of jawbone model, and (b): geometrical characteristics of the bone.

The influence of the mandible thickness on the location of the fracture and the propagation of cracks was examined. The XFEM method in ABAQUS software was used to investigate the effect of the thickness of the mandible and its relationship with the rate of crack propagation in the bone. The site of fracture propagation was not pre-established, and its initiation point was presumed to be at the location of maximum stress.

2.2. Numerical Procedure

The materials used for the cancellous and cortical bone regions are assumed to be viscoelastic and heterogeneous. The cortical and cancellous bones have Young's moduli of 14.4 and 0.480 GPa, respectively. Additionally, the Poisson ratios of cancellous and cortical bones are 0.4 and 0.3, respectively [14-15]. The critical damage initiation strain and stress are supposed to be 0.0004 and 50, respectively [14-15]. For cortical bone, the values of the plastic deformation coefficients are given in “Table 2”. In the viscoelastic models, the Prony series parameters are used because the materials behave close to the Maxwell model in this case [16]. The assumed delay period is 50 minutes, and the treatment period is assumed to be 4300 hours, which represents approximately 6 months [17]. The support at the end of the jawbone was assumed to be completely constrained and fixed [20-21]. The upper surface of the bone in the body area was subjected to a force of 100 N [17], [22-24].

Table 2 The cortical bone plastic properties [14-15]

Stress [MPa]	Strain [mm/mm]
99.54	0
110.37	0.00081
120.93	0.00233
125.31	0.00471
128.15	0.00724
130.89	0.00977
134.39	0.01225
137.13	0.01474
140.8	0.017235

The muscle force loading was applied dynamically to the bone areas. The values of muscle forces are provided in “Table 3” [15], [18]. Muscle forces were also assumed to be distributed evenly over the muscle areas [19].

Table 3 The muscle force loading

Muscle	Force value [N]
Masseter	59.23
Medial pterygoid	39.60
Lateral pterygoid	33.44
Temporal	34.09
Suprahyoid	10

The loading of forces in different areas is shown in “Fig. 2”.

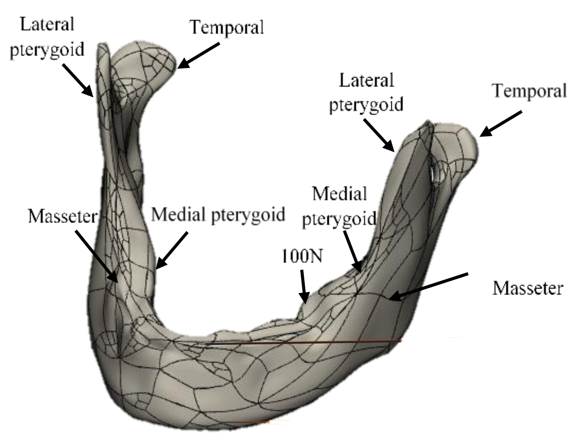

Fig. 2 Jawbone loading forces exerted by muscles.

To apply dynamic loads, a chewing action model with a chewing interval ranging from 1 to 0.6 seconds, with an average of 0.8 seconds, was considered. Note that the chewing interval varies depending on the type of food, and these values are considered in the case of normal foods.
To apply the described loading, the loadings determined in each part are divided into small parts consisting of 57 ramp functions, which together constitute the described loadings. To investigate bone fracture and crack propagation, the C3D20R nonlinear element type was used [23].
ABAQUS software has the ability to generate a suitable mesh for efficiently simulating various mechanical problems. For this purpose, the capabilities of the ABAQUS software were used to generate the computational mesh in this study, and a computational mesh was generated considering the physics of the problem. The FREE element method was used due to the complex geometry of the studied components. Figure 3 illustrates the generated mesh, which consists of 510,007 elements.

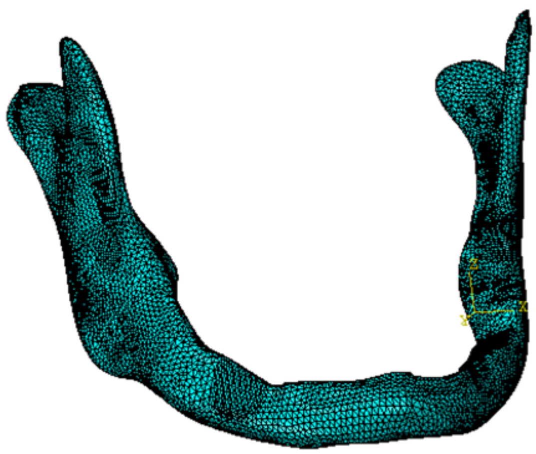

Fig. 3 Computational mesh used in finite element analysis.

3 RESULTS

In this study, crack propagation in a precise geometry of an edentulous, resorbed jawbone is investigated using finite element analysis. ABAQUS software is employed to conduct FEM. Findings are analyzed considering the von Mises stress and the crack propagation created in the jawbone. In this section, first, the Von Mises stress distribution in the mandible at different jawbone thicknesses is investigated. Next, the formation and propagation of cracks in these models are studied. Also, the impact of cracks on the stress distribution in various regions is investigated.

3.1. Von Mises Stress Distribution

Figure 4 depicts the von Mises stress in the jawbone with different thicknesses. By increasing the jawbone thickness, the maximum value of the von Mises stress decreases. For example, increasing jawbone thickness from 10.2 to 11 results in a decrease in the maximum von Mises stress from 999.3 to 119.2 MPa. Additionally, the stress distribution becomes more uniform as the thickness of the jawbone decreases. It is also observed that in all thicknesses of the jawbone examined, the minimum von Mises stress occurs in the condylar neck.

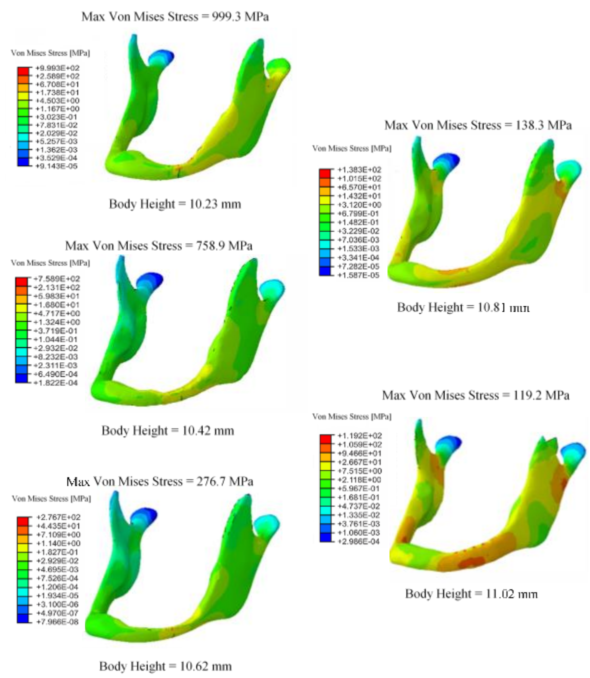

Fig. 4 Von Mises stress created in mandibular bone in 5 different thicknesses.

3.2. Crack Propagation

As discussed, the maximum stress in the jawbone occurs in the bone body. Depending on the thickness of the jaw, the amount of this maximum stress and its effect on the formation and propagation of cracks vary. Figure 5 shows the crack propagation at different jawbone thicknesses. The crack propagation decreases with increasing bone thickness. For example, in a bone model with a thickness of 10.2 mm, the maximum stress generated is 999.3 MPa; in this case, the jawbone exhibits the highest crack propagation rate in the body region. By increasing the thickness to 10.4 mm, the maximum stress generated is reduced to 758.9 MPa, resulting in reduced crack propagation at this thickness. By further increasing the thickness of the jaw in the body region to 10.6 mm, the maximum stress generated is reduced to 276.7 MPa. Due to the reduction in thickness and the type of loads applied to the bone (as in the previous two thicknesses), the concentration of stress in the bone body region caused the crack to spread in this thickness. Increasing the thickness to 10.8 mm resulted in a maximum stress of 138.3 MPa, and at this thickness, the amount of crack spread is very small. Finally, the 11 mm thick jawbone experiences the maximum stress of 119 MPa in the bone body. At this thickness, despite the concentration of stress in the bone body, no crack was observed.

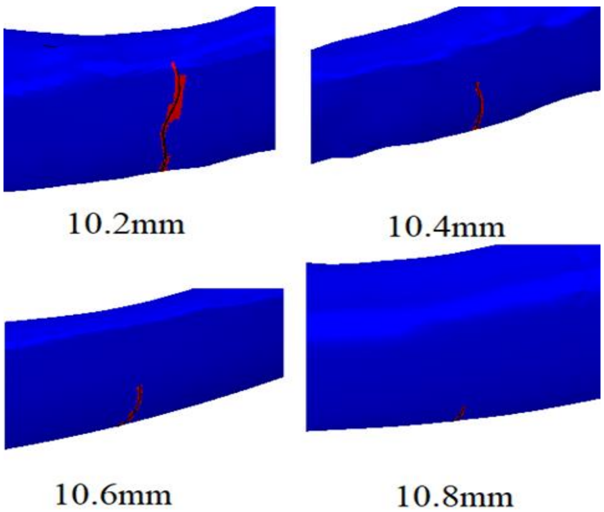

Fig. 5 Crack formation and propagation in the bone body at different thicknesses.

5 DISCUSSIONS

The finite element method is utilized to investigate the stress distribution and fracture propagation in the mandible [16], [25]. This form of numerical investigation is a highly beneficial tool for developing novel biomaterials and enhancing surgical techniques. Indeed, numerical modeling can offer more effective solutions for the diagnosis and management of mandibular bone diseases [13], [26]. In cases where complete and properly positioned teeth are present in the dentition, chewing forces are distributed evenly across the teeth, and the generated stresses may not be applied to the condylar neck; however, a patient with a resorbed jawbone and no teeth may apply higher chewing forces, which causes more stress on the mandible.

Examination of stress distribution in the jawbone at different thicknesses shows that the stress distribution is more uniform at smaller thicknesses. Also, the maximum stress occurs in the bone body region. Cracks are thus anticipated to appear in this area. According to the stress analysis in the 11 mm thick jawbone, the maximum von Mises stress occurs in the body and ramus regions. With a decrease in the thickness of the bone body, due to the formation of cracks in the bone, the concentration of stress is transferred to the bone body region. In fact, with a decrease in the thickness of the bone body, the maximum stress increases, and the jawbone begins to crack in the body region. Following the formation of the crack, the maximum stress is generated at the location of the crack.

5 CONCLUSIONS

Findings of this work revealed that the maximal von Mises stress decreases as the thickness of the mandible bone increases. Additionally, when estimating mandibular bone fracture, individuals with an edentulous resorbed jawbone may experience a fracture due to muscle chewing forces if the mandibular bone thickness is less than 10.8 mm. However, if the bone thickness increases to 11 mm, the probability of fracture decreases. The results were obtained in accordance with the chewing pattern in the standard state and may be subject to modification as the chewing cycle is altered.

REFERENCES

[1] Choi, K. Y., Yang, J. D., Chung, H. Y., and Cho, B. C., Current Concepts in the Mandibular Condyle Fracture Management Part I: Overview of Condylar Fracture, Arch. Plast. Surg., Vol. 39, No. 04, 2012, pp. 291-300, doi: https://doi.org/10.5999/aps.2012.39.4.291.

[2] Kyzas, P. A., Saeed, A., and Tabbenor, O., The Treatment of Mandibular Condyle Fractures: A Meta-Analysis, Journal of Cranio-Maxillofacial Surgery, Vol. 40, No. 8, 2012, pp. e438-e452.

[3] Wennerberg. A., and Albrektsson, T., Current Challenges in Successful Rehabilitation with Oral Implants, Journal of Oral Rehabilitation, Vol. 38, No. 4, 2011, pp. 286-294.

[4] Ellis E., Dean, J., Rigid Fixation of Mandibular Condyle Fractures, Oral Surgery, Oral Medicine, Oral Pathology, Vol. 76, No. 1, 1993, pp. 6-15.

[5] Derfoufi, L., Delaval, C., Goudot, P., and Yachouh, J., Complications of Condylar Fracture Osteosynthesis, Journal of Craniofacial Surgery, Vol. 22, No. 4, 2011, pp. 1448-1451.

[6] Ellis, E., Throckmorton, G. S., Treatment of Mandibular Condylar Process Fractures: Biological Considerations, J. Oral Maxillofac. Surg., Vol. 63, No. 1, 2005, pp. 115-134, doi: https://doi.org/10.1016/j.joms.2004.02.019.

[7] Iizuka, T., Lindqvist, C., Hallikainen, D., Mikkonen, P., and Paukku, P., Severe Bone Resorption and Osteoarthrosis after Miniplate Fixation of High Condylar Fractures: A Clinical and Radiologic Study of

Thirteen Patients, Oral surgery, oral medicine, oral pathology, Vol. 72, No. 4, 1991, pp. 400-407.

[8] Rallis, G., Mourouzis, C., Ainatzoglou, M., Mezitis, M., and Zachariades, N., Plate Osteosynthesis of Condylar Fractures: A Retrospective Study of 45 Patients, Quintessence international, Vol. 34, No. 1, 2003.

[9] Vollmer, D., Meyer, U., Joos, U., Vegh, A., and Piffkò, J., Experimental and Finite Element Study of a Human Mandible, Journal of Cranio-Maxillofacial Surgery, Vol. 28, No. 2, 2000, pp. 91-96.

[10] Kavanagh, E., Frawley, C., Kearns, G., Wallis, F., Mc Gloughlin, T., and Jarvis, J., Use of Finite Element Analysis in Presurgical Planning: Treatment of Mandibular Fractures, Irish Journal of Medical Science, Vol. 177, 2008, pp. 325-331.

[11] Hedeșiu, M., Pavel,D. G., Almășan, O., Pavel, S. G., Hedeșiu, H., and Rafiroiu, D., Three-Dimensional Finite Element Analysis on Mandibular Biomechanics Simulation under Normal and Traumatic Conditions, Oral, Vol. 2, No. 3, 2022, pp. 221-237.

[12] De Mello Santos, L. S., Rossi, A. C., Freire, Matoso, R. I., Caria, P. H. F., and Prado, F. B., Finite-Element Analysis of 3 Situations of Trauma in the Human Edentulous Mandible, Journal of Oral and Maxillofacial Surgery, Vol. 73, No. 4, 2015, pp. 683-691.

[13] Costa, F. W. G., Bezerra, M. F., Ribeiro, T. R., Pouchain, E. C., Sabóia, V. D. P. A., and Soares, E. C. S., Biomechanical Analysis of Titanium Plate Systems in Mandibular Condyle Fractures: A Systematized Literature Review, Acta Cirúrgica Brasileira, Vol. 27, 2012, pp. 424-429.

[14] Klotch, D. W., Lundy, L. B., Condylar Neck Fractures of the Mandible, Otolaryngologic Clinics of North America, Vol. 24, No. 1, 1991, pp. 181-194.

[15] Haug, R. H., Peterson, G. P., and Goltz, M., A Biomechanical Evaluation of Mandibular Condyle Fracture Plating Techniques, J. Oral Maxillofac. Surg., Vol. 60, No. 1, 2002, pp. 73-80.

[16] Meyer, C., Serhir, L., and Boutemi, P., Experimental Evaluation of Three Osteosynthesis Devices Used for Stabilizing Condylar Fractures of the Mandible, Journal of Cranio-Maxillofacial Surgery, Vol. 34, No. 3, 2006, pp. 173-181.

[17] Fernández, J. R., Gallas, M., Burguera, M., and Viano, J., A Three-Dimensional Numerical Simulation of Mandible Fracture Reduction with Screwed Miniplates, J. Biomech., Vol. 36, No. 3, 2003, pp. 329-337.

[18] Meyer, C., Kahn, J. L., Boutemi, P., and Wilk, A., Photoelastic Analysis of Bone Deformation in the Region of the Mandibular Condyle During Mastication, Journal of Cranio-Maxillofacial Surgery, Vol. 30, No. 3, 2002, pp. 160-169.

[19] Asprino, L., Consani, S., and De Moraes, M., A Comparative Biomechanical Evaluation of Mandibular Condyle Fracture Plating Techniques, Journal of oral and maxillofacial surgery, Vol. 64, No. 3, 2006, pp. 452-456.

[20] O. C. Zienkiewicz, R. L. Taylor, and M. C. Ruiz, El Método De Los Elementos Finitos. McGraw-Hill Barcelona, 1994.

[21] M. Champy, M., JP, L., Étude Des Contraintes Dans La Mandibule Fracturée Chez L'homme: Mesures Théoriques Et Vérification Par Jauges Extensométriques in Situ, 1977.

[22] Haim, D., Müller, A., Leonhardt, H., Nowak, A., Richter, G., and Lauer, G., Biomechanical Study of the Delta Plate and the Trilock Delta Condyle Trauma Plate, Journal of oral and Maxillofacial Surgery, Vol. 69, No. 10, 2011, pp. 2619-2625.

[23] Lauer, G., Pradel, W., Schneider, M., and Eckelt, U., A New 3-Dimensional Plate for Transoral Endoscopic-Assisted Osteosynthesis of Condylar Neck Fractures, J. Oral Maxillofac. Surg., Vol. 65, No. 5, 2007, pp. 964-971.

[24] Vajgel, A., Camargo, I. B., Willmersdorf, R. B., De Melo, T. M., Laureano Filho, J. R., and De Holanda Vasconcellos, R. J., Comparative Finite Element Analysis of the Biomechanical Stability of 2.0 Fixation Plates in Atrophic Mandibular Fractures, Journal of Oral and Maxillofacial Surgery, Vol. 71, No. 2, 2013, pp. 335-342.

[25] Sugiura, T., Yamamoto, K., Murakami, K., and Sugimura, M., A Comparative Evaluation of Osteosynthesis with Lag Screws, Miniplates, or Kirschner Wires for Mandibular Condylar Process Fractures, Journal of Oral and Maxillofacial Surgery, Vol. 59, No. 10, 2001, pp. 1161-1168.

[26] Wagner, A., Krach, W., Schicho, K., Undt, G, Ploder, O., and Ewers, R., A 3-Dimensional Finite-Element Analysis Investigating the Biomechanical Behavior of the Mandible and Plate Osteosynthesis in Cases of Fractures of the Condylar Process, Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, Vol. 94, No. 6, 2002, pp. 678-686.