Injury 55 (2024) 112020

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

A finite element analysis of the trapezoidal plate. How to get a stable fixation at different fracture lines?

Paris Liokatis [a], Georgios Tzortzinis [b], Carl Peter Cornelius [e], Yoana Malenova [c,*], Katharina Theresa Obermeier [c], Wenko Smolka [d]

[a] Department of Oral & Maxillofacial Surgery, University of Munich, LMU, Germany
[b] Institute of Lightweight Engineering and Polymer Technology, Dresden University of Technology, Germany
[c] Department of Oral & Maxillofacial Surgery, University of Munich, Lindwurmstr. 2a, LMU D-80337, Germany
[d] Vice Director, Department of Oral & Maxillofacial Surgery, University of Munich, LMU, Germany
[e] Affiliated Professor, Department of Oral & Maxillofacial Surgery, University of Munich, LMU, Germany

ARTICLE INFO

Keywords:
Condylar fracture
Internal fixation
Finite element analysis
Trapezoidal plate

ABSTRACT

The fractures in the condylar area are a challenge for every surgeon, for the treatment of which trapezoidal condylar plate is used in most cases. However, it is not possible to position the plate in the ideal osteosynthesis lines according to Meyer et al. in every clinical situation. In many cases, the fracture line is also not in the centre of the trapezoidal plate. The aim of this study is to investigate the osteosynthesis rigidity and the effect of plate localisation relative to the fracture line.

In a simulation model in the first group the plate was positioned in the ideal position in the middle of the condylar base, in the second group the plate position was changed - the plate was shifted upwards until the fracture passed underneath the centre of the plate again and in the last group the plate was moved further down so that the fracture passes underneath the middle of the plate. Heterogeneity of the bone was simulated using different sets of biomechanical properties.

In the experiment, the joints were fully constrained and a force of 500 N was applied to the opposite side. An interaction between bone and plate was completely excluded and the stability of the plates as well as the mobility of the bone fragments was analysed.

The results have shown that an inferior position of the fracture line leads to greater mobility of the fragments if the position of the osteosynthesis material is the same. With a deep fracture line, a more cranial positioning of the plate leads to better stabilisation. This study needs to be experimentally validated.

Introduction

The condylar area is a biomechanically challenging part of the mandible. This complexity is reflected in the variety of classifications and terminology that exist to describe fractures, with the goal of providing clinicians with principles for successful treatment. Furthermore, various plate designs aim to provide a broader range of options for effectively treating these fractures.

Among these designs, the trapezoidal condylar plate (TCP) stands out as one of the most commonly used for osteosynthesis of mandibular condylar fractures . Originally introduced by Meyer et al. in 2007, this plate was specifically designed to follow the strain pattern observed in the condylar region during function [2,3].

In an effort to understand the biomechanical behaviour of different three-dimensional plates, FEA studies were performed, too. However, these studies have often yielded contradictory results when comparing the trapezoidal plate to other designs. This suggests that there is no singular perfect plate design, and that additional parameters beyond ideal osteosynthesis lines must be considered for successful osteosynthesis [4–7].

In clinical practice, surgeons frequently encounter situations where they must deviate from placing the trapezoidal plate along the ideal osteosynthesis lines as described by Meyer et al. [8]. Moreover, in many cases, the fracture line does not cross beneath the middle of the

Short title: Finite element analysis of trapezoidal condylar plates

* Corresponding author.
E-mail address: Yoana.Malenova@med.uni-muenchen.de (Y. Malenova).

https://doi.org/10.1016/j.injury.2024.112020
Accepted 7 November 2024
Available online 9 November 2024

trapezoidal plate, which is considered as the optimal relationship [3]. In such circumstances, questions naturally arise regarding whether the plate placement offers sufficient rigidity, or if an alternative position should be pursued to mitigate even sporadic failures.

The aim of the present study is to examine the osteosynthesis rigidity when trapezoidal plates are utilized for fractures at different levels within the condylar base area. Additionally, we aim to assess how slight alterations in plate positioning relative to the fracture line impact osteosynthesis stability for a given fracture.

Materials and methods

This study was approved by the ethic committee of the University Hospital of Munich (LMU Munich, Germany; No. 19–783).

Model generation

A thin sliced (0.625 mm) CT scan of a healthy person was used. ProPlan CMF software suite (DePuy Synthes Maxillofacial) was used to create a model of the bony mandible from the CT images by appropriate segmentation to remove the soft tissues. The initial model was cut in the left condyle to simulate three typical condylar base fractures running from the incisura semilunaris posteriorly and down to the posterior ramus. All cuts were made parallel to each other at a distance of 5 mm. A gap of 0.2 mm was created between the fragments. All three fractures can be classified as fractures of the condylar base according to the AO—Classification [9]. The upper fracture was designed to be above the sigmoid notch line by approximately one-third-as seen from a lateral view, to cover the uppermost condylar base fractures according to the AO—Classification (Fig. 1 and 2) [9].

Three comparison groups were produced according to the following protocol:

In the first group, the trapezoidal plate was placed in an ideal position in the middle of the condylar base. The three fractures passed underneath the center, the upper and lower third of the plate. The rigidity of the osteosynthesis was examined for the three fractures, by examining the mobility of the fragments along the fracture.

In the second group, the fracture in the upper third of the plate from the first group remained unchanged, and the plate was shifted upwards until the fracture passed underneath the center of the plate again. The stability of the osteosynthesis was examined for the changed plate placement at this fracture.

In the third group, the fracture in the lower third of the plate from group one was used. Analogous to group two, the plate was moved further down so that the fracture passes underneath the middle of the plate. The stability of the osteosynthesis was then examined for the altered plate placement.

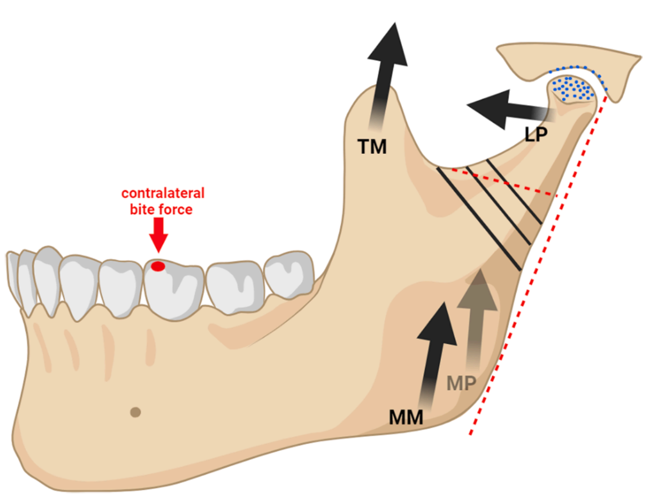

Fig. 1. Loading conditions of the finite element model of the mandible. LP lateral pterygoid, MP: medial pterygoid, TM: temporal muscle, MM: masseteric muscle, blue dots at condylar head: constrains.

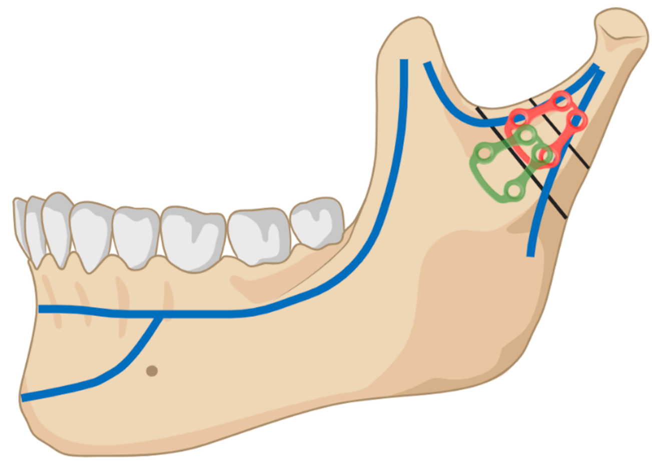

Fig. 2. The upper and lower fractures are indicated with black. The middle fracture is not shown. Upper (red) and lower (green) position of the trapezoidal plate relative to the ideal osteosynthesis lines (blue).

The three-dimensional surface model of the trapezoidal plate, provided by the manufacturer (DePuy Synthes, Paoli, PA), was attached to the mandible using cylindrical screws designed by the researchers to be analogous to a 6 $\times$ 2 mm non-locking screw.

Geometry definition

A convergence test was performed to determine the appropriate number and geometry of the surface elements [10]. A denser mesh was used in the fracture area to allow a more detailed simulation of the biomechanical behaviour. The number of mesh elements was approximately 400,000 for each model with a second-order tetrahedral geometry, and a side length of 0,3 mm of the tetrahedra in the area of interest.

Material properties assignment

Since bone is highly inhomogeneous and to simulate this heterogeneity, twelve different sets of biomechanical properties were assigned to it based on its density [11–13], which can be calculated from the grayscale of each voxel in the CT scan using the Hounsfield equation [14]. The experimentally described equations for the femur were used for these conversions, as corresponding formulas for the mandible are missing [11,15] . The osteosynthesis material (plate and screws) was considered homogeneous, and the properties of the titanium alloy Ti-6AI-4 V were assigned to them ($E = 114$ GPa; $\nu = 0{,}34$) [16].

Loading conditions

A maximum bite force of 500 N was applied to the occlusal surface of the contralateral (right) molar [17]. The reaction forces of the masticatory muscles were then calculated according to experimental findings (Fig. 1) [18,19]. The upper surfaces of both condylar heads were fully constrained. The forces occurring in the bone were transmitted to the plate via the screws, and no direct interaction between the plate and bone was allowed.

Evaluation

The stability of the different osteosynthesis patterns were evaluated by calculating the movement of the bony segments at the fracture line using the software ABAQUS (Simulia, Dassault Systèmes). Perren et al.

suggested a displacement threshold of approximately < 0,150 μm as a criterion for successful fracture healing [20].

Further parameters such as strains in the bone or in the material were not considered in this study since an increased mobility of the fragments is an indicator of higher strains in the bone, too [28]. In addition to this, failure of the plate is not a common complication since mainly loosening of the screws is observed [1], which is again a secondary consequence of increased mobility of the fragments leading to bone resorption [28].

Results

For the same plate placement, the mobility of the condylar fragments increased with a more inferior position of the fracture line in the area of the condylar base (Fig. 3). The displacement of the fragments significantly exceeded the critical limit only in the most inferior fracture pattern.

Further examination of the uppermost (Fig. 3a) and lowermost (Fig. 3c) fractures revealed that the mobility of the fragments changed when a different plate placement was considered. The mobility at the upper fracture was further reduced with a more cranial placement of the plate (4b). However, on the other hand, the mobility increased with a more caudal placement of the plate at the lower fracture (5b).

Model a. The fracture is located underneath the upper third of the plate.
Model b. The fracture is crossing underneath the middle of the plate.
Model c. The fracture is crossing underneath the lower third of the plate.

Only in the lowest fracture (model c) the critical threshold of displacement of 0.15 mm is significantly exceeded at the fracture area (yellow and orange colours), which leads to an increased risk of non-healing.

Fig. 4, 5

Model a. This placement of the plate seems to improve the rigidity of the osteosynthesis, by reducing displacement (fracture area shifts from yellow to green colour).
Model b. This placement of the plate seems to worsen the rigidity of the osteosynthesis, by increasing displacement (fracture area shifts from orange/yellow to red colour). The critical threshold of 0.15 mm is significantly exceeded at the fracture line, which may lead to non-healing

Discussion

The trapezoidal plate is one of the most commonly used in the condylar base of the mandible, but there are still open questions about its ideal application and its biomechanical behaviour when treating different fracture patterns. Although in some non-randomized studies, no bone healing disturbances among patients treated with TCP have been reported [21–23], other researchers have noted sporadic failures when utilizing TCP [1,24,25]. However, in the limited prospective randomized studies aimed at eliminating selection bias, neither Adhikari et al. [26] nor Kumar et al. [27], with 26 and 10 patients treated with TCP respectively, reported any bone healing disturbances

In this paper, we evaluated the change in the rigidity of the osteosynthesis for different plate placements and fracture locations in the condylar base area.

We found that the plate performs more effectively for upper condylar base fractures. Further improvement in osteosynthesis rigidity is achievable for these fractures by positioning the plate higher, ensuring the fracture lies underneath the middle section of it. For lower condylar base fractures, optimal stability is achieved when the fracture lies underneath the lower third rather than the middle part of the plate, meaning that a higher placement of the plate should be pursued in these cases, as well.

According to these findings, the following practical suggestions could be made:

- for condylar base fractures near or crossing the sigmoid notch line the plate should be placed as cranially as possible. However, positioning the plate higher, could become difficult due to the lateral prominence of the condylar head and the thin condylar neck, which do not allow an uncomplicated placement of the plate and the two upper screws [7]. This prevented a more cranial plate placement in our model in order for the fracture to pass underneath the lower third of the plate.
- For fractures located below the sigmoid notch line, a more cranial plate placement should be pursued as well, in order for the fracture line to lie underneath the lower third of the plate.

The second recommendation regarding lower fractures is contradictory to the empirical intraoperative aim of placing the plate in a manner that the fracture passes underneath its middle part. The worst rigidity found for these fractures could be due to the plate being at an increased distance from the ideal osteosynthesis lines, as it moves more caudally. The trapezoidal plate was designed to follow the osteosynthesis lines, but due to its small size, this is not possible for lower base fractures, where the lines diverge. This could also explain the better rigidity for upper base fractures found in this study. Similar FEA findings were shown for other plates designed to follow these lines as well [28]. Another reason could be the longer proximal fragment, resulting in increased lever loads at the fracture line when the fracture is located more caudally. A possible solution for both explanations could be a bigger trapezoidal plate, allowing its limbs to be closer to the diverging posterior ramus und sigmoid notch osteosynthesis lines even at lower base fractures.

These findings suggest that the osteosynthesis lines recommended by Meyer et al. [8] are of increased importance for neutralizing tensile and compression stresses in the critical condylar area. Nevertheless, even when plates are placed consistently along these lines, variations in fracture patterns can result in differing levels of rigidity [29].

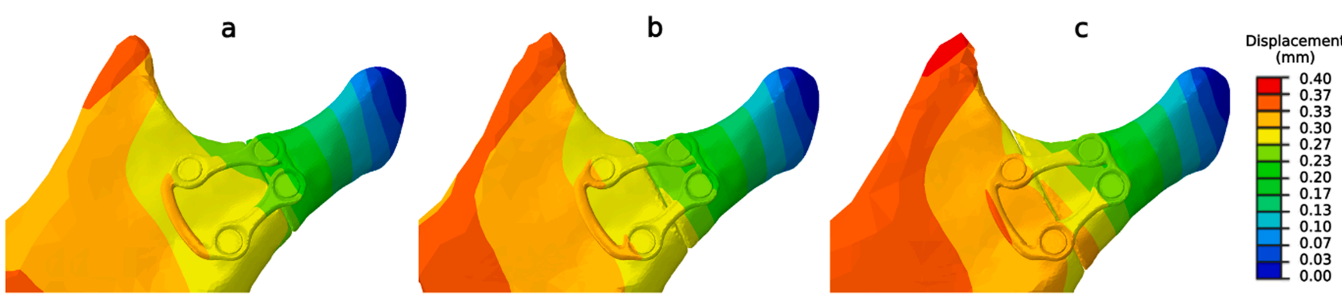

Fig. 3. Displacement of the bone fragments for three different fracture lines while the position of the plate remains unchanged. The blue and green colours indicate a lower mobility of the fragments, which according to Perren et al. promotes bone healing. Similarly, yellow, orange and red colours indicate a higher fragment mobility, that could disturb healing.

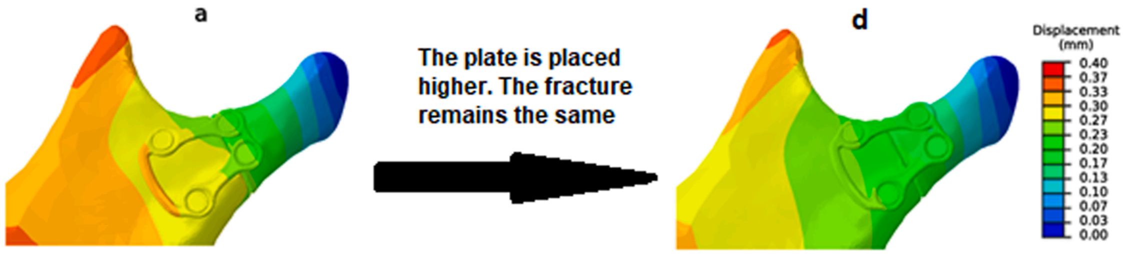

Fig. 4. The model (a) from the previous figure (Fig. 3) is further examined, by moving the plate higher in order for the fracture to be underneath the middle of the plate, generating model (d).

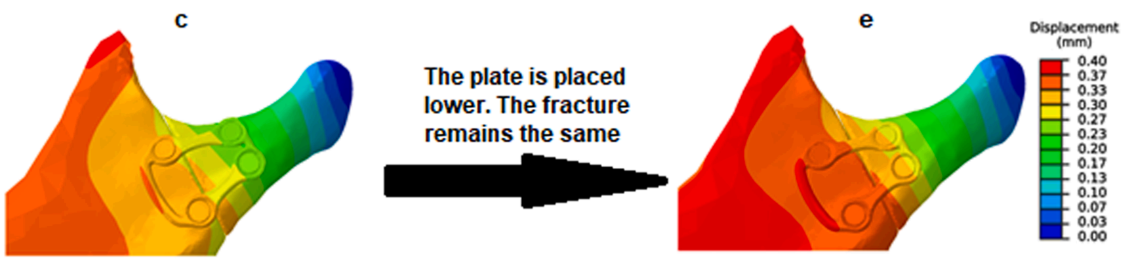

Fig. 5. The model (c) from Fig. 3 is further examined, by moving the plate lower in order for the fracture to be underneath the middle of the plate, generating model (e).

The findings of this study should be considered for further improving the stability of the osteosynthesis and reducing the risk of non-union. The current findings suggest that the plate can, in most cases, offer an adequate rigidity for fractures in the condylar base, especially if the surgeon shows flexibility with its placement, as mentioned above.

This study has the limitations of FEA studies and it is not experimentally validated. Moreover, the equations used for assigning the biomechanical properties in the bone originate from data from the femoral bone, since appropriate equations are not adequately described for the mandible. Furthermore, we applied a maximum bite force of 500 N on the model, but in many cases, postoperative loading is significantly restricted for a period of up to six weeks [30]. Additionally, we examined the displacement of the fragments as the most critical parameter for undisturbed bone healing. Further parameters such as strains in the bone or in the material could be considered.

Declaration of generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the authors didn't any AI or AI-assisted technologies in the writing process.

Ethics statement

This study was approved by the ethic committee of the University Hospital of Munich (LMU Munich, Germany; No. 19–783).

CRediT authorship contribution statement

Paris Liokatis: Writing – original draft, Visualization, Software, Data curation, Conceptualization. **Georgios Tzortzinis:** Writing – original draft, Software, Formal analysis, Data curation. **Carl Peter Cornelius:** Supervision, Methodology. **Yoana Malenova:** Writing – original draft, Formal analysis. **Katharina Theresa Obermeier:** Writing – original draft, Visualization, Formal analysis. **Wenko Smolka:** Supervision, Methodology.

Declaration of competing interest

The authors declare no conflict of interest.

References

[1] Smolka W, Liokatis P, Cornelius CP. Evaluation of complications after open reduction and internal fixation of mandibular condylar base and neck fractures using trapezoidal plates. J. Craniofac. Surg. 2020.
[2] Meyer C, Serhir L, Boutemi P. Experimental evaluation of three osteosynthesis devices used for stabilizing condylar fractures of the mandible. J. Craniomaxillofac. Surg. 2006;34(3):173–81.
[3] Meyer C, et al. Development and biomechanical testing of a new osteosynthesis plate (TCP) designed to stabilize mandibular condyle fractures. J. Craniomaxillofac. Surg. 2007;35(2):84–90.
[4] Albogha MH, Mori Y, Takahashi I. Three-dimensional titanium miniplates for fixation of subcondylar mandibular fractures: comparison of five designs using patient-specific finite element analysis. J. Craniomaxillofac. Surg. 2018;46(3): 391–7.
[5] Darwich MA, et al. Assessment of the biomechanical performance of 5 plating techniques in fixation of mandibular subcondylar fracture using finite element analysis. J. Oral Maxillofac. Surg. 2016;74(4). 794 e1-8.
[6] de Jesus GP, et al. Finite element evaluation of three methods of stable fixation of condyle base fractures. Int. J. Oral Maxillofac. Surg. 2014;43(10):1251–6.
[7] Liokatis P, et al. Finite element analysis of different titanium plates for internal fixation of fractures of the mandibular condylar neck. J. Oral Maxillofac. Surg. 2021;79(3). 665 e1-665 e10.
[8] Meyer C, et al. Photoelastic analysis of bone deformation in the region of the mandibular condyle during mastication. J. Craniomaxillofac. Surg. 2002;30(3): 160–9.
[9] Neff A, et al. The comprehensive AOCMF classification system: condylar process fractures - level 3 tutorial. Craniomaxillofac. Trauma Reconstr. 2014;7(Suppl 1): S044–58.
[10] Viceconti M, et al. Extracting clinically relevant data from finite element simulations. Clin. Biomech. (Bristol,. Avon) 2005;20(5):451–4.
[11] Cong A, Buijs JO, Dragomir-Daescu D. In situ parameter identification of optimal density-elastic modulus relationships in subject-specific finite element models of the proximal femur. Med. Eng. Phys. 2011;33(2):164–73.
[12] O'Mahony AM, et al. Anisotropic elastic properties of cancellous bone from a human edentulous mandible. Clin. Oral Implants Res. 2000;11(5):415–21.
[13] Misch CE, Qu Z, Bidez MW. Mechanical properties of trabecular bone in the human mandible: implications for dental implant treatment planning and surgical placement. J. Oral Maxillofac. Surg. 1999;57(6). 700-6; discussion 706-8.
[14] Rho JY, Hobatho MC, Ashman RB. Relations of mechanical properties to density and CT numbers in human bone. Med. Eng. Phys. 1995;17(5):347–55.
[15] Keyak JH, et al. Prediction of femoral fracture load using automated finite element modeling. J. Biomech. 1998;31(2):125–33.
[16] Yang D, Liu Z. Quantification of Microstructural Features and Prediction of Mechanical Properties of a Dual-Phase Ti-6Al-4V Alloy. Materials. (Basel) 2016;(8): 9.

[17] Braun S, et al. A study of bite force, part 1: relationship to various physical characteristics. Angle Orthod. 1995;65(5):367–72.
[18] Pruim GJ, de Jongh HJ, ten Bosch JJ. Forces acting on the mandible during bilateral static bite at different bite force levels. J. Biomech. 1980;13(9):755–63.
[19] Korioth TW, Hannam AG. Mandibular forces during simulated tooth clenching. J. Orofac. Pain. 1994;8(2):178–89.
[20] Perren, S.M., Physical and biological aspects of fracture healing with special reference to internal fixation. Clin. Orthop. Relat. Res., 1979(138): p. 175–96.
[21] Palani T, et al. Evaluation of 3D Trapezoidal Plates in Open Reduction and Internal Fixation of Subcondylar Fractures of Mandible: a Clinical Trial. Cureus. 2021;13 (6):e15537.
[22] Sikora M, et al. The use of 3D titanium miniplates in surgical treatment of patients with condylar fractures. J. Clin. Med. 2020;9(9).
[23] Chaudhary M, et al. Evaluation of trapezoidal-shaped 3-D plates for internal fixation of mandibular subcondylar fractures in adults. J. Oral Biol. Craniofac. Res. 2015;5(3):134–9.
[24] Vajgel A, et al. Treatment of condylar fractures with an intraoral approach using an angulated screwdriver: results of a multicentre study. J. Craniomaxillofac. Surg. 2015;43(1):34–42.
[25] Burkhard JP, et al. Perioperative predictors of early surgical revision and flap-related complications after microvascular free tissue transfer in head and neck reconstructions: a retrospective observational series. Clin. Oral Investig. 2021;25 (9):5541–50.
[26] Adhikari M, et al. Fixation of subcondylar fractures of the mandible: a randomized clinical trial comparing one trapezoidal plate with two miniplates. Int. J. Oral Maxillofac. Surg. 2021;50(6):756–62.
[27] Kumar S, et al. Treatment outcome comparison between two 3-dimensional plates (Y-shaped plate versus trapezoidal condylar plate) in management of mandible condylar fracture: a randomized control trial. J. Maxillofac. Oral Surg. 2023;22(1): 25–32.
[28] Liokatis P, et al. Application of the lambda plate on condylar fractures: finite element evaluation of the fixation rigidity for different fracture patterns and plate placements. Injury 2022;53(4):1345–52.
[29] Liokatis P, et al. Finite element analysis of different titanium miniplates: evaluation of three-dimensional designs applied on condylar neck fractures. J. Stomatol. Oral Maxillofac. Surg. 2021.
[30] 3rd Tate GS, Ellis E, Throckmorton G. Bite forces in patients treated for mandibular angle fractures: implications for fixation recommendations. J. Oral Maxillofac. Surg. 1994;52(7):734–6.