ORIGINAL RESEARCH ORİJİNAL ARAŞTIRMA

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Carbon Fiber Reinforced PEEK Compared to Titanium Alloys for Temporomandibular Joint Trauma Surgery: An Experimental Study

Temporomandibular Eklem Kondil Kırıklarının Tedavisinde Kullanılan Karbon Fiber ile Güçlendirilmiş PEEK ve Titanyum Alaşımlarının Karşılaştırılması: Deneysel Çalışma

Senanur DURUAY ALKAN[a], Sıdıka Sinem AKDENIZ[a], Ezgi ERGEZEN[b]

[a]Private Dentist, Ankara, Türkiye
[b]Başkent University Faculty of Dentistry, Department of Oral and Maxillofacial Surgery, Ankara, Türkiye

ABSTRACT Objective: Temporomandibular joint fractures are very common however there is not a consensus on the treatment protocol. As the tendency towards open reduction and internal fixation increase, alternative fixation materials have drawn attention. The aim of the present study is to acknowledge if 60% carbon fiber reinforced polyetheretherketone (Cfr-PEEK) material can be used as an alternative for titanium alloys for the temporomandibular joint (TMJ) fracture fixation. **Material and Methods:** High and low TMJ subcondylar fractures were simulated on a finite element model. Rhombic plate and 2- plate systems were designed in titanium and 60% Cfr-PEEK. Stress in the fixation materials, bone and the displacement of the fragments were evaluated. **Results:** For high subcondylar fracture the rhombic plate system presented better results compared to 2- plate system contrary to low subcondylar fracture fixation. Regarding the material choice 60% Cfr-PEEK presented superior results compared to titanium alloys for low subcondylar facture and similar results with titanium alloys for high subcondylar fractures. The displacement of the fragments was lower in 60% Cfr-PEEK models for each fixation system. **Conclusion:** Cfr-PEEK can be an alternative for titanium alloys for TMJ fracture fixation especially considering its biomechanical properties can be optimized for clinical conditions nevertheless these findings should be supported with further studies for widespread use.

Keywords: PEEK; carbon fiber reinforced-PEEK; temporomandibular joint fracture; condyle fractures; finite element analysis

ÖZET Amaç: Bu çalışmanın amacı, %60 karbon fiber ile güçlendirilmiş polietereterketon [carbon fiber-reinforced polyetheretherketone (Cfr-PEEK)] materyalinin temporomandibular eklem (TME) kırık fiksasyonu için titanyum alaşımının alternatifi olarak kullanılıp kullanılamayacağını belirlemektir. **Gereç ve Yöntemler:** Sonlu elemanlar modelinde yüksek ve düşük seviyeli TME subkondiler kırıkları simüle edildi. Titanyum ve %60 Cfr-PEEK'ten oluşan rombik plaka ve 2 plak sistemi tasarlandı. Fiksasyon malzemelerindeki stres, kemik ve parçaların yer değiştirmesi değerlendirildi. **Bulgular:** Yüksek subkondiler kırık için rombik plaka sistemi, düşük subkondiler kırık sabitlemesine kıyasla 2 plak sistemine göre daha iyi sonuçlar gösterdi. Malzeme seçimi açısından, %60 Cfr-PEEK, düşük subkondiler kırık için titanyum alaşımlarına kıyasla üstün sonuçlar sunarken, yüksek subkondiler kırıklar için titanyum alaşımları ile benzer sonuçlar verdi. Parçaların yer değiştirmesi, her fiksasyon sistemi için %60 Cfr-PEEK modellerinde daha azdı. **Sonuç:** Cfr-PEEK, özellikle biyomekanik özellikleri klinik koşullar için optimize edilebilir olduğu düşünülerek, TME kırık fiksasyonu için titanyum alaşımlarının bir alternatifi olabilir; ancak bu bulguların yaygın kullanım için daha fazla çalışma ile desteklenmesi gerekmektedir.

Anahtar Kelimeler: PEEK; karbon fiber ile güçlendirilmiş-PEEK; temporomandibular eklem kırık; kondil kırığı; sonlu elemanlar analizi

Treatment of condylar fracture is one of the most controversial topics which is commonly occur after maxillofacial traumas.[1] Although the facial nerve located around the subcondylar area and it is under a risk of damage during surgical intervention of temporomandibular joint (TMJ), open reduction and in-

Correspondence: Ezgi ERGEZEN
Başkent University Faculty of Dentistry, Department of Oral and Maxillofacial Surgery, Ankara, Türkiye
E-mail: ezgiergezen@gmail.com

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ternal fixation (ORIF) has become the standardized treatment choice.[2] ORIF is preferred as it allows for better reduction of the fragments and the early function of the patient.[3] Different fixation systems have been proposed in the literature such as bicortical screws, single plate, double plate, 3D plates and the tendency towards 3D plates and double plate has become prominent.[4]

The success of the rigid fixation systems depends on the stress distribution on plate, screws and bone.[4] Titanium and its alloys are mostly used as fixation materials due to their biocompatibility and long term reliability, however titanium is associated with failure and tissue reactions.[5] To reduce these unwanted effects of titanium implants including stress-shielding osteolysis, new fixation materials such as polyetheretherketone (PEEK) which is a polyaromatic semi-crystalline thermoplastic polymer have been introduced.[6] Later developed to carbon fiber reinforced-PEEK (Cfr-PEEK) with favorable properties for bio-medical applications.[6] The advantage of Cfr-PEEK is that its Young's modulus is closer to the jaw bone, giving the material superior biomechanical properties.[7]

Finite element analysis (FEA) is used for understanding mechanical behaviors of bony structures. Stress and strain patters as well as displacement of the bone fragments under functional loading can be determined by FEA and creating a precise mathematical model of vital tissues.[8-10]

Cfr-PEEK have already been used in orthopedic, spine and craniomaxillofacial surgery due to its biocompatibility, similar biomechanical properties with bone, convenience for radiographic imaging and esthetic appearance.[11] However biomechanical properties of Cfr-PEEK have never been evaluated for TMJ fracture fixations.

The aim of this study is to evaluate the stress in cortical bone and displacement of the fracture fragments, fixed with either 2 mini plate or rhomboid plate fixation with Cfr-PEEK or titanium alloy materials in high- and low-level subcondylar fractures with FEA.

MATERIAL AND METHODS

Başkent University institutional review board approved the present study in 2022 (project no. D-DA21/06). A 3-dimensional finite element model of a human mandible was generated by a computer with Windows 7 Ultimate Service Pack operating system and Intel Xeon CPU 3.30 GHz processor was used for the evaluations. Activity 880 (smart optics Sensortechnik GmbH, Sinterstrasse 8, D-44795 Bochum, Germany) optical scanner, VRMesh Studio (VirtualGrid Inc, Bellevue City, WA, USA) and Algor Fempro (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238-2932 USA) was used for the analysis. The mechanical properties were defined for the bone and fixation systems separately and the cortical bone was assumed to be anisotropic, homogeneous and linearly elastic.

Subcondylar fractures were designed in two different levels as low and high. Low subcondylar fracture was designed as the fracture line from the middle height of the ramus to the sigmoid notch. High subcondylar fracture was designed as a more horizontal line compared to the low fracture line starting from posterior border of the to the sigmoid notch.

Fixation units have been designed as titanium alloys and 60% Cfr-PEEK, and fitted to mandibula using Rhinoceros version 4.0 software (3670 Woodland Park Ave N, Seattle, WA 98103 USA). Rhomboid plate (Titanium and PEEK osteosynthesis mandibula; KLS Martin, Tuttlingen, Germany) and 2 mini plates (AO Compact MF Lock System Implant; Johnson & Johnson) system were designed compatible with the manufacturers' instructions. Both high and subcondylar fractures were fixated with 2 different fixation systems and 4 models were created; 1) high level- titanium rhomboid, 2) high level- Cfr-PEEK rhomboid, 3) low level- titanium 2 plate, 4) low level- Cfr-PEEK rhomboid. The screws were numbered for easy reference (Figure 1).

150-N/mm^2 load was applied with a 60^o angle with the horizontal plane to the condyle head. The von Mises stress values (N/mm^2) of the hardware, maximum and minimum principal stress (N/mm^2) values of the bone around the fixation units and the displacement (mm) of the fragments were evaluated for each fixation model (1 Gpa=1000 N/mm^2).

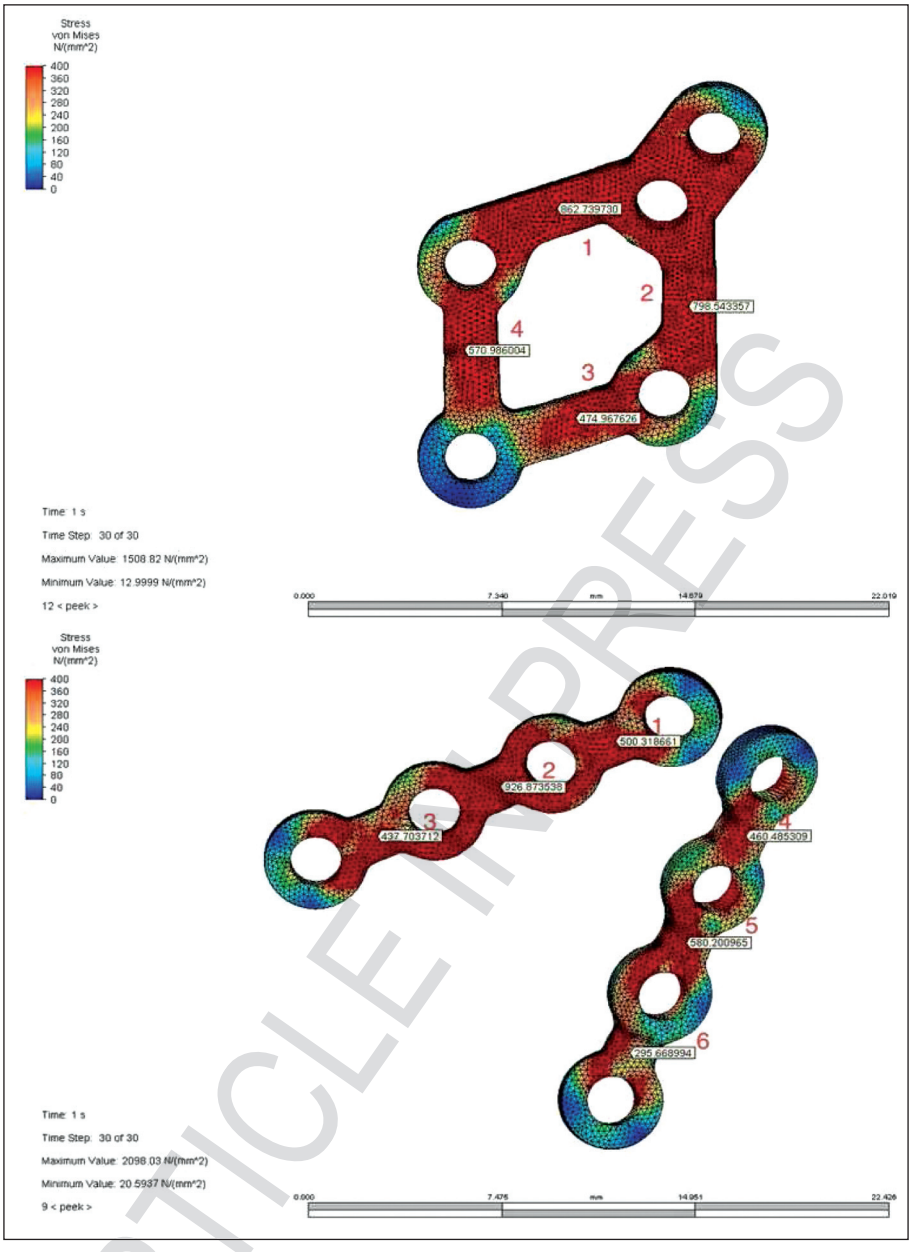

FIGURE 1: Plate fixation systems- numbered.

RESULTS

STRESS DISTRIBUTION IN HIGH SUBCONDYLAR FRACTURE WITH RHOMBIC FIXATION MODEL

The von Misses stress values was higher in Cfr-PEEK model compared to the titanium, and concentrated closer to the sigmoid notch and the fracture line (Figure 2). The highest tension was measured in titanium plate around the 1st screw and the highest compression was measured in Cfr-PEEK plate around the 3rd screw (Figure 3, Figure 4). Maximum displacement was measured in the titanium plate (Figure 5).

STRESS DISTRIBUTION IN LOW SUBCONDYLAR FRACTURE WITH RHOMBIC FIXATION MODEL

The von Misses stress values was higher in Cfr-PEEK model compared to the titanium, and concentrated closer to the posterior border of the ramus and

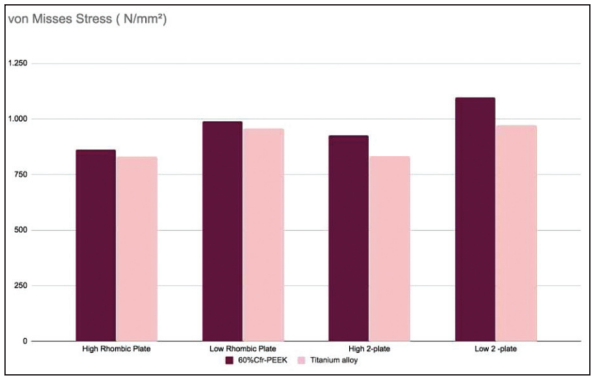

FIGURE 2: von Mises stress values measured in the fixation systems.

the fracture line (Figure 2). The highest tension was measured in titanium plate around the 2nd screw and the highest compression was measured in Cfr-PEEK plate around the 1st screw (Figure 3, Figure 4). Maximum displacement was measured in the titanium plate (Figure 5).

STRESS DISTRIBUTION IN HIGH SUBCONDYLAR FRACTURE WITH 2-PLATE FIXATION MODEL

The von Misses stress values was higher in Cfr-PEEK model compared to the titanium, and concen-

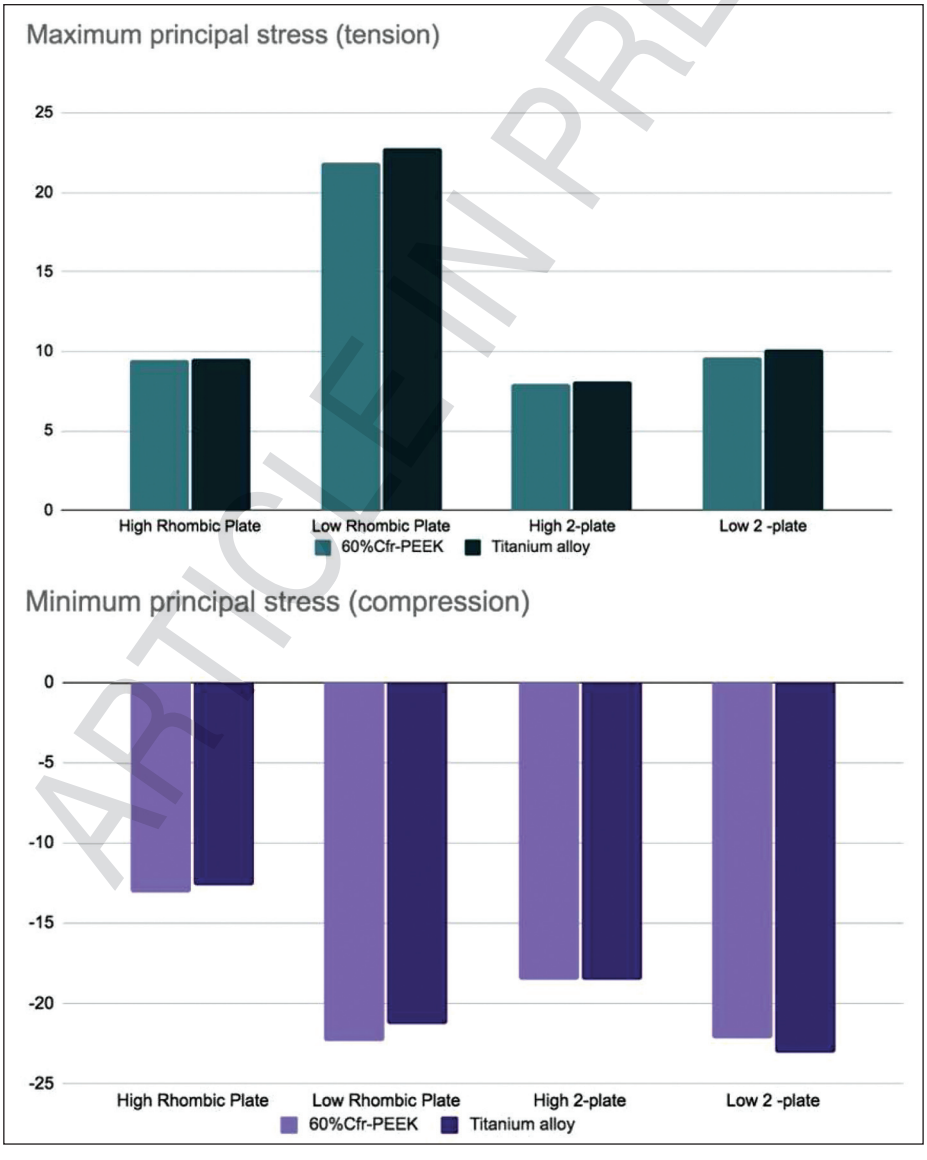

FIGURE 3: Maximum and minimum principal stress values in the cortical bone.

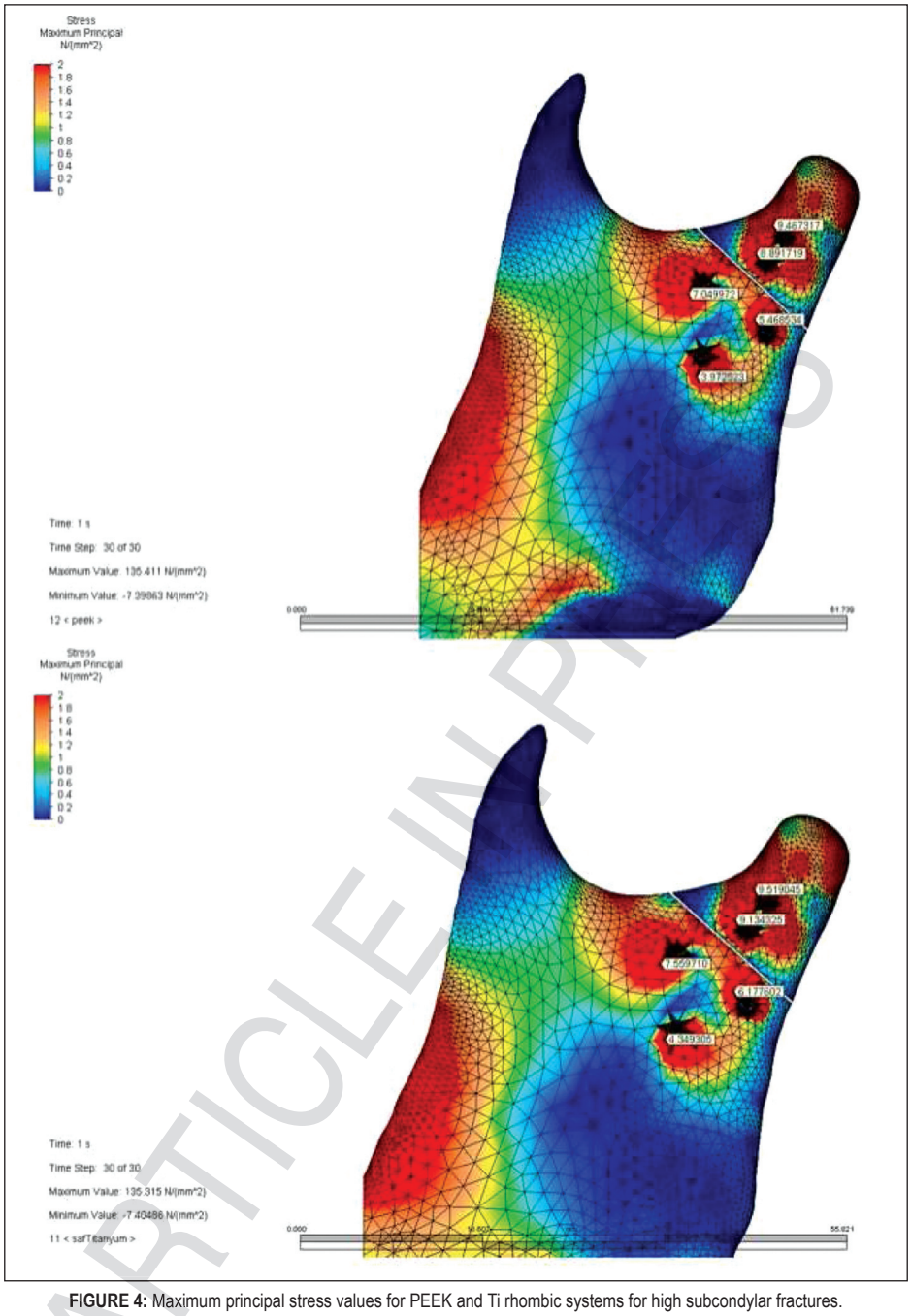

FIGURE 4: Maximum principal stress values for PEEK and Ti rhombic systems for high subcondylar fractures.

trated closer to the sigmoid notch and the fracture line (Figure 2). The highest tension was measured in titanium plate around the 1st screw and the highest compression was measured in titanium plate around the 5th screw (Figure 3, Figure 6). Maximum displacement was measured in the titanium plate (Figure 5).

STRESS DISTRIBUTION IN LOW SUBCONDYLAR FRACTURE WITH 2-PLATE FIXATION MODEL

The von Misses stress values was higher in Cfr-PEEK model compared to the titanium, and concentrated closer to the sigmoid notch and the fracture line (Figure 2). The highest tension was measured in titanium plate around the 1st screw and the highest com-

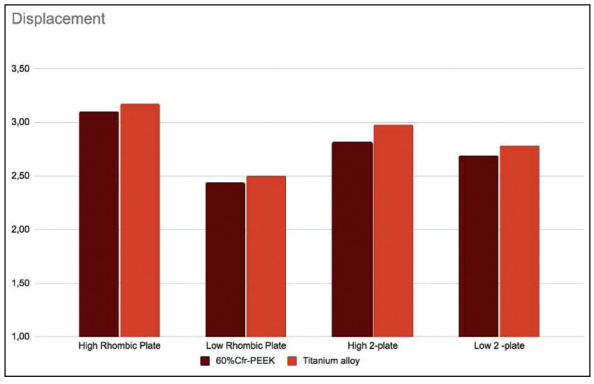

FIGURE 5: Displacement values of the fragments.

pression was measured in titanium plate around the 5th screw (Figure 3, Figure 6). Maximum displacement was measured in the titanium plate (Figure 5).

DISCUSSION

This study compared stress distributions of 2 different plates systems for 2 different subcondylar fracture levels with FEA. The results of this study suggested that the Cfr-PEEK 2-plate system can be considered as an alternative for titanium 2-plate system for low level subcondylar fractures. Rhombic plate system showed better results for high condylar fractures biomechanically however, the Cfr-PEEK material for rhombic plate was not significantly superior compared to titanium.

As the tendency towards ORIF for TMJ fractures have increased, the search for a better design and material for the fixation devices increased as well.[12] The similarity between the elastic properties of bone and fixation material is important for homogenous load sharing between these components.[13] The human cortical bone has tensile strength of 104-121 MPa and Young's Modulus of 14 GPa, 60% Cfr-PEEK has tensile strength and Young's Modulus of 120 MPa and 18 Gpa which is compatible with cortical bone's mechanical properties.[14,15]

Considering the Cfr-PEEK has superior mechanical and physical properties similar to bone compared to titanium (110 Gpa), it was introduced as an alternative.[16,17] Compared to 30% Cfr-PEEK, 60% carbon reinforcement increased the elastic modulus and the tensile strength. Thus, biomechanical properties of the 60% Cfr-PEEK was suggested to be closer to that of human cortical bone.[6,18] Also the Cfr-PEEK is a radiolucent material which makes it easier to evaluate the fracture healing radiographically.[19]

Cfr-PEEK has been successfully used for craniofacial reconstruction, orthopedic, spinal and cardiac surgery.[6] A recent FEA study compared Cfr-PEEK material for the fixation of mandibular angulus fracture with titanium and resorbable plates, results showed that 2 mm Cfr-PEEK plate can be considered as an alternative to 1 mm titanium plate.[20] However, in our study the von Misses values were higher in Cfr-PEEK plates which may be due to the unique loading pattern of the TMJ. In addition to tensional and compressional forces, shear forces are high in mandibular condyle.[21]

The results of this study revealed that the rhombic plate is superior compared to two miniplate system for high subcondylar fractures. Regarding the material choice, fixation with Cfr-PEEK rhombic plate showed similar tension and compression stress values. Hence the stress distribution in the bone was well-balanced for this fixation system. Also the displacement values measured in Cfr-PEEK plates were lower compared to titanium systems, which should be considered for clinical application. However, the von Misses stress was higher in Cfr-PEEK compared to titanium which can lead to fatigue failure but the difference between the stress values were too insignificant for considering an increase in the stress shielding effect.

Two-plate system showed more homogenous stress distribution compared to rhombic design for low subcondylar fracture, possible explanation is that the 2-plate system forms a wider fixation plane, resulting more stable fixation.[22,23] Cfr-PEEK 2-plate system for fixation of low subcondylar fracture showed comparable results with titanium 2-plate system. Von Misses stress values in Cfr-PEEK material were also slightly higher and displacement values were lower as high subcondylar fracture fixation systems. Based on this result Cfr-PEEK material can be considered as an alternative for the fixation of low subcondylar fractures.

Compression stress on bone have been shown to induce osteoclast-mediated bone resorption.[24] The

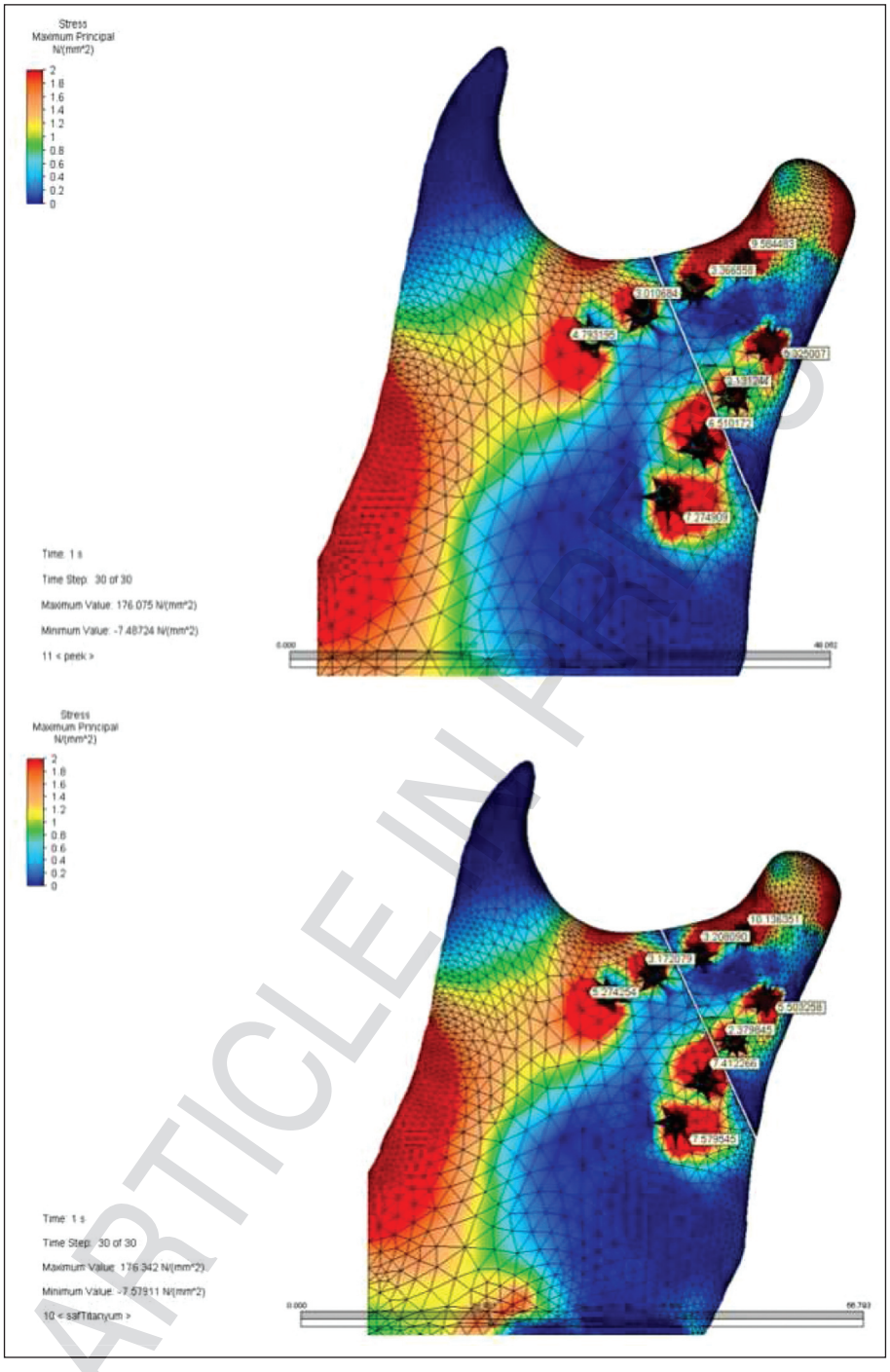

FIGURE 6: Minimum principal stress values for PEEK and Ti 2-Plate systems for low subcondylar fractures.

success of the fixation system is mainly dependent on the stress distribution between plate, screws and the surrounding bone. Minimizing stress in the bone surrounding the screw hole will reduce the risk of screw loosening. All of the compressional stress values around the screws were lower than the critical threshold (56 MPa), which is mostly concentrated around the screws closer to the fracture line in the condylar part and the posterior border of the ramus.[25]

Cfr-PEEK material did not present significantly better results for mandibular subcondylar fractures in the present study, as literature suggested for the fix-

ation of the mandible angle or the atrophic jaws. However, it can be considered as a promising alternative material for titanium alloys. Since its mechanical properties can be modified as needed, Cfr-PEEK fixation systems are open to improvement for the fixation of TMJ area. Also the limitations of FEA studies duplicating the clinical conditions should be considered; postoperative muscle strength change, callus formation and the effect of soft tissue was ignored in this study.

CONCLUSION

Considering the evaluated fragment displacement and tension parameters on bone, Cfr-PEEK material can be considered to have an advantage over titanium alloys for TMJ subcondylar fractures since these values were lower for all the scenarios. Hence Cfr-PEEK can be considered as an alternative for titanium alloys for fixation of the TMJ subcondylar fracture, as its structure can be developed to increase the biomechanical and biological properties. Composite polymers, including PEEK can be optimized for oral and maxillofacial applications and these findings should be supported with further comparative mechanical and long term clinic studies.

Source of Finance

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Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

Idea/Concept: *Sıdıka Sinem Akdeniz, Senanur Duruay Alkan;* ***Design:*** *Sıdıka Sinem Akdeniz, Senanur Duruay Alkan;* ***Control/Supervision:*** *Sıdıka Sinem Akdeniz;* ***Data Collection and/or Processing:*** *Senanur Duruay Alkan;* ***Analysis and/or Interpretation:*** *Sıdıka Sinem Akdeniz, Senanur Duruay Alkan, Ezgi Ergezen;* ***Literature Review:*** *Sıdıka Sinem Akdeniz, Senanur Duruay Alkan, Ezgi Ergezen;* ***Writing the Article:*** *Sıdıka Sinem Akdeniz, Senanur Duruay Alkan, Ezgi Ergezen;* ***Critical Review:*** *Sıdıka Sinem Akdeniz;* ***References and Fundings:*** *Senanur Duruay Alkan.*

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