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ORIGINAL ARTICLE / ARAŞTIRMA MAKALESİ

Biomechanical Comparison of Two Types of Compression Screws Using Finite Element Analysis and Servo-Hydraulic Testing Unit: An Ex Vitro Study

Mandibular Simfiz Fraktürlerinde Kullanılan İki Farklı Kompresyon Vidasının Biyomekanik Özelliklerinin Sonlu Elemanlar Analizi ve Servohidrolik Test Ünitesi ile Değerlendirilmesi ve Karşılaştırması: Ex Vitro bir Çalışma

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ABSTRACT

Objectives: Various types of fixation systems have been developed to stabilize the fractured fragments in their original position. The purpose of this ex vitro study was to compare the biomechanical properties of 2 fixation units provided by different types of second-generation headless cannulated compression screws (SG-HCCS) using a servo-hydraulic testing unit (STU) and finite element analysis (FEA).

Materials and Methods: Fourteen fresh frozen sheep cadaveric mandibles were divided into 2 groups randomly(n=7). 3.0 milimeters (mm) diameter, 20mm length partially threaded Herbert screws were used in Group 1 and 2.8mm diameter, 20mm length fully threaded HCCS were used in Group 2 for the fixation of the fragments that was made by a vertical osteotomy at the midline. 2 screws were placed in each model, parallel to each other but in opposite directions. All models were examined biomechanically for the stability of fixation by using STU and FEA.

Results: Both FEA and STU analysis revealed that the forces required to fail the fixation system provided by HCCS were significantly higher than Herbert screws.

Conclusions: Within the limits of this experimental study, the findings suggest that the biomechanical adequacy provided by second-generation compression screws may be a promising alternative in the treatment of mandibular symphysis fractures, aided by the favorable anatomy of the region. The study may also be useful for further studies in terms of evaluating and comparing different fixation systems in virtual environments using FEA.

Keywords: Bone screws, compression, finite element analysis, fracture fixation,mandible.

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ÖZ

Amaç: Kırık parçaları orijinal pozisyonlarında sabitlemek için çeşitli fiksasyon sistemleri geliştirilmiştir. Bu ex vitro çalışmanın amacı, bir servohidrolik test ünitesi (STU) ve sonlu elemanlar analizi (SEA) kullanılarak 2 farklı tasarıma sahip ikinci nesil başsız kanüllü kompresyon vidaları kullanılarak oluşturulan fiksasyonun biyomekanik özelliklerini karşılaştırmaktı.

Gereç ve Yöntemler: On dört adet taze dondurulmuş koyun kadavra alt çenesi rastgele 2 gruba ayrıldı (n=7). Mandibular simfiste orta hatta vertikal osteotomi ile kırık hattı oluşturuldu. Oluşturulan kırık fragmanların fiksasyonu için Grup 1'de 3,0 mm çapında, 20 mm uzunluğunda kısmen yivli Herbert vidaları, Grup 2'de ise 2,8 mm çapında, 20 mm uzunluğunda tam yivli HCCS vidaları kullanıldı. Her modele birbirine paralel ancak zıt yönlerde 2 adet vida yerleştirildi. Tüm modeller, STU ve SEA kullanılarak fiksasyonun stabilitesi açısından biyomekanik olarak incelendi.

Bulgular: Hem SEA hem de STU analizleri, HCCS kullanılarak oluşturulan fiksasyonun bozulması için gereken kuvvetlerin Herbert vidalarından istatistiksel olarak anlamlı derecede yüksek olduğu gözlemlendi.

Sonuç: Bu deneysel çalışmanın sınırları dahilinde, bulgular, ikinci nesil kompresyon vidalarının sağladığı biyomekanik yeterliliğin, bölgenin uygun anatomisinin de yardımıyla mandibular simfiz kırıklarının tedavisinde umut verici bir alternatif olabileceğini düşündürmektedir. Çalışma ayrıca SEA kullanılarak sanal ortamlarda farklı sabitleme sistemlerinin değerlendirilmesi ve karşılaştırılması açısından ileriki araştırmalara da faydalı olabilir.

Anahtar Kelimeler: Çene kırıkları, kırık sabitlenmesi, mandibula, sonlu eleman analizi.

INTRODUCTION

Mandibular fractures occur more frequently than any other facial fracture, because the mandible is the most prominent and the only mobile bone of the facial skeleton. Among mandibular fractures, mandibular symphysis fracture were reported as the most common (Brasileiro et.al.,2009). The key factors in managing a fracture are the stabilization and fixation of fracture segments.To provide a optimal fixation, various fixation systems have been developed up to date, ranging from wires to pins, plates and screws (Franz,2009).

Lag screw osteosynthesis in mandibular symphysis fractures is a well-established technique known for its effectiveness in providing stability due to its high compressive capability.However, a notable drawback of lag screws is bone resorption and tissue irritation caused by protrusion of the screw head. To prevent this, various modifications to screw design have been developed over time. Second generation cannulated compression screws (SG-HCCS) are one example of such modifications. Nonetheless, it was reported that the modifications in screw designs may compromise their biomechanical properties (Kozakiewicz,2018).

The aim of this study was to compare the biomechanical properties of two different designed SG-HCCSs—Herbert and HCCS—using a servo-hydraulic test unit (STU) and finite element analysis (FEA).

MATERIALS AND METHODS

This study was carried out in accordance with the principles of the Declaration of Helsinki. The study protocol was reviewed and approved by the Institutional Animal Care and Use Committee of Marmara University (Istanbul, Turkey) with the approval number: 07.2014.mar dated 20.02.2014. Fourteen fresh sheep cadaveric mandibles were used in this study. The soft tissues of all mandibles were stripped off, and a linear vertical osteotomy was performed in the midline at the symphysis region using a micro-saw under saline irrigation. The samples were randomly divided into 2 experimental groups (n=7). In Group-1, 3.0mm diameter 20mm length cannulated Herbert screws *(TST Medical Devices, Istanbul, Turkey)* and in Group-2 2.8mm diameter 20mm length cannulated HCCS *(TST Medical Devices, Istanbul, Turkey)* were used for the fixation of the fragments. In each mandible 2 screws were placed, perpendicular to the osteotomy line, parallel but in an opposite direction to each other, 2-3 mm away from the apex of the anterior teeth.

Servohydraulic Tests

To set the experimental station properly, a pilot mandible model was generated by a 3D printer *(Flashforge creator, USA)* and a custom-made stainless steel holder was manufactured according to the model. Acrylic resin polymers were used to embed the angulus portions and fix the samples to the holder. All samples were examined in the STU *(Testometric M500 30 kn, Testometric Company Ltd. England)* for the following properties:

1. Maximum force (MF): The maximum force (N) that the fixation unit could tolerate before failure of the fixation.
2. Maximum displacement (MD): The amount of maximum displacement (mm) of the fractured fragments just before the screws slipping out from the bone.

The STU was calibrated with a 0.1 N pre-load force. To increase the sensitivity of the test, the displacement was arranged as 0.1 mm/minute. A continuous force, beginning from 0 N and increasing with a constant acceleration (0,1 mm displacement/minute) was applied perpendicular to the osteotomy line, until the stability of the fixation system failed as a result of the deformation of the screw, plate, or models. The data obtained from the STU were simultaneously transferred to computer and force-displacement graphics were formed by the Testometric Software (*Testometric Company Ltd. England)*. For all samples, MF and MD were recorded.

Finite Element Analysis

FEA was initiated with post-op CT scans (0.5-mm sections in DICOM format) and followed by reverse engineering that can be described as converting the CT scans into solid models for computer supported engineering procedures. The data gained from the CT scan were saved as .stl data using MIMICS 10.01 *(Materialise, Leuven, Belgium)*. For editing and refinement of the data, CATIA V5 R17 *(Computer Aided Three-dimensiosnal Interactive Application, Dassault Systèmes, France)* was used. The material properties of the bone and screws in the model were defined according to experimental data from a previous study (Korkmaz,2007). Appropriate boundary conditions were imposed using Ansys Workbench 14.5 *(ANSYS Inc, PA, USA)*. (Table 1) To obtain accurate results, the finite element model (FEM) was meshed into 10-nodal 132053 tetrahedral finite elements and 213500 nodes. Frictional contact was applied as the type of contact. FEA tests are applied virtually to simulate biomechanical tests. The amount and distribution of maximum stress (MS) in the symphysis region, osteotomy line and screw were recorded under 100 N force.

Table 1. The material properties of the bone and screws (Korkmaz, 2007).

Material properties	Bone	Screw (Ti6A14V)
Elastic modulus	13700 MPa	113800 MPa
Poisson Ratio (v)	0.3	0.342
Yield strength	100 MPa	880 MPa

Statistical Analysis

Statistical analysis were performed using SPSS 21.0 *(IBM Corp, US)* software. Shapiro-Wilk test was used to test the compliance of the data with normal distribution and Mann-Whitney U test was used to compare non-normally distributed variables. Results were evaluated at the $p< 0.05$ significance level, in 95% confidence interval (95% CI).

RESULTS

In the STU, MF ranged between 100-238N for Group-1 and 90-250N for Group-2. The MD ranged between 2-12mm for Group-1 and 5-12mm for Group-2. (Table-2)

Table-2. MF and MD values that recorded in STU.

Metrics	MF (N)			MD (mm)		
Groups	Median (IQR)	Mean rank	Sum of rank	Median (IQR)	Mean rank	Sum of rank
Group-1	107,00	5,29	37,00	5,00	3,29	35,50
Group-2	138,00	9,21	68,00	12,00	7,20	69,60
	*U=9,00 (p=0,047 p<0,05)			*U=7,50 (p=0,026 p<0,05)		

In FEA, MS under 100 N was measured as 107.05 MPa in Group-1. Considering that this value was greater than the bone's yield strength (107.05 MPa > 100 MPa), the fixation was predicted to fail. The stress occurring on the Herbert screw was measured as 120 MPa. As this average value was much smaller than the yield strength of the titanium screw (120 MPa < 880 MPa), the titanium screw was not expected to be damaged. In Group 2, MS under 100 N was measured as 102.75 MPa. Since this value was greater than the bone's yield strength (102.75 MPa > 100 MPa), the fixation unit was expected to fail. MS occurring on the HCCS was measured as 322.56 MPa. Since this value was much smaller than the yield strength of the titanium screw (120 MPa < 880 MPa), no damage was expected to the titanium screw.

DISCUSSION

Compression screws were reported as the most efficient tools for approximating fracture sites and enhancing stability through the generation of interfragmentary pressure (Franz,2009). Different modifications of a compression screw with the same diameter and length result in variable anchorage in the bone (Kozakiewicz & Sołtysiak,2017). We aimed to evaluate the stability of fixation provided by 2 differently designed SG-HCCS. Our null hypothesis was that a screw with a fully threaded design would increase friction along the fracture line and promote compression of the fragments, thus improving resistance against destructive forces. This study revealed that fixation provided by the 2.8 mm diameter HCCS was more able to withstand destructive forces than the 3.0 mm diameter Herbert screw.

The resistance of a screw to destructive stress is affected by various factors, including its profile, design, diameter, sharpness, and the number of threads (Galuppo et.al.,2002). HCCS and Herbert screws share common features including being headless, cannulated, conical in shape (narrowing from head to apex), titanium (Ti6A14V) made, self-cutting and self-tapping. The modified design of these screws offers several advantages. Being headless, eliminates the necessity for countersinking, which can lead to screw loosening and compromise stability. The ability to embed the leading and trailing tips into the drilled path minimizes irritation to the surrounding soft tissues (Kozakiewicz & Sołtysiak,2017). These 2 SG-HCCSs differ in terms of thread design: the HCCS is threaded along its entire long axis, whereas Herbert screw has no threads on the middle third. Rahpeyma et al. reported that the blank shaft in the center of Herbert screws allowed the approximation of fractured fragments without preventing their reduction but also the continuous thread design of the HCCS confers of greater compression compared to partially threaded Herbert-style screw designs (Rahpeyma,2016).

Mandibular symphysis was identified as an appropriate area for the screw fixation with the absence of any important vascular or neural anatomical structures. The curvature of interforaminal region allows for the accommodation of the entire length of the screw into the bone for the fixation of fractures. Further, thick cortical bone of the symphysis ensures secure subcortical placement and rigid fixation (Ram et.al.,2017). A significant handicap in the management of symphyseal fractures is the high degree of torsional stress (Budhraja et. al.,2018). One screw was reported to be insufficient to prevent the rotational movement of the fracture fragments and the fragments may undergo torsion and shear forces. In the present study, we placed 2 screws in opposite directions in the horizontal plane, to prevent rotation, as recommended in the literature (Booth et.al.,2003).

The use of SG-HCCSs in maxillofacial surgery appears to be focused mainly on condylar head fractures, with limited indications (Kozakiewicz,2018).To the best of our knowledge, only a few studies have described the use of SG-HCCSs in the treatment of mandibular symphysis fractures. El-Mahallawy et.al. reported that the fixation provided by HCCSs was a successful and minimally invasive treatment modality for the management of anterior mandibular fractures (El-Mahallawy&Al-Mahalawy,2018). Sheep cadaveric mandibles are commonly used in such studies due to their similarity in thickness and size to the human mandibles (Haug et.al.,2002). Van Hareen et al. reported there were no changes in the mechanical properties of preserved cadaveric animal bones which had been frozen and treated with 10% formaldehyde, and reported that they could be used safely in mechanical tests for up to one year of storage (van Haaren et al.,2008). We preferred to use sheep cadaveric mandibles because of their advantages and all samples were kept at –15°C in 10% formaldehyde solution throughout the study. Faran et al. compared the compressive forces of Herbert and HCCS on cancellous bone discs transected from fresh human cadavers and found no significant difference statistically but mathematically the resistance to tensile forces was found 42% higher in the HCCS group (Faran et. al.,1999). They concluded that HCCS could be used preferably to Herbert screw in the young population, considering the correlation between cortical density and the compression of the screw. In contrast, Adla et al. compared 3.0 mm Herbert and 2.0 mm HCCS on cancellous bone models and found no significance between the compressions of the screws (Adla et. al.,2005). This may be a result of the large difference in the screws' diameters. We aimed to examine the screws' biomechanical properties as objectively as possible by choosing their diameters closer to each other. Despite their relatively smaller diameter, HCCS exhibited statistically higher MF, MD, and MS values in STU and FEA than Herbert screws. The fully threaded design and profile of HCCS may be the cause of this difference.

In vivo studies were reported to be insufficient for fully understanding of the biomechanical effects of the inherent properties of the mandible, such as elasticity and density, and the vector of masticatory forces, including magnitude and direction (Shyam Sundar et. al.,2012). To assess the fixation unit ex vitro, biomechanical experimental and hypothetical techniques can be used. STU and FEA were reported to be the most common analysis methods for strain and stress analysis of different types of fixation systems (Atalı et. al.,2014). In the biomechanical test units, the most challenging part is realistically performing the masticatory forces (Adla et. al.,2005).

2 methods can be used to assess the displacement and maximum force that the fixation unit can withstand without deforming: applying predetermined forces or applying an incremental force with a constant acceleration, starting from 0 N and stopping when deformation occurs. In this study, similar to previous studies, a 100 N predetermined force was applied to the FEMs in FEA, as in a previous study (Bayram et. al.,2009), while an incremental force with a constant acceleration (starting from 0 N and stopping when deformation occurs) was applied in STU (Peterson et. al.,2005).

FEA was reported to be a reliable and convenient method for assessing stress distribution and clinical performance of complex geometric systems. A definite correlation between ex vitro studies and FEA studies using mandible models has been reported in many studies. In FEA, the analysis becomes easier to perform, as the object becomes simpler and vice versa. When it comes maxillofacial structures, the analysis can be challenging due to the complex nature. Hence, the modeling step is important in FEA for maxillofacial surgery (Bayram et. al.,2009). The accuracy of FEA results relies on the similarity between the original biological structure and FEM, the quantity of nodes and the clearly defined boundary conditions. In the present study, the models were meshed into 132053 tetrahedral finite elements and 213500 nodesto obtain the proximate results. Since the element and node values of the FEM created in this study are close or higher than those of similar studies (Castaño et.al.,2002) it was not necessary to make a convergence test for the models.

This study was limited by several factors. In STU, only one type loading protocol were used. Although the sample size was determined based on a previous study (Ram et al.,2017), larger samples could potentially yield more comprehensive results. Furthermore, it is important to consider that the anatomical and physical characteristics of the sheep cadaveric mandibles differ from those of humans. Besides, the absence of muscle attachments in the cadaveric mandibles could have been altered the biomechanic characteristics of the fixation unit comprising the screw and bone. An experimental setting that closely imitates the human mandible with its surrounding soft tissues and masticatory muscles may be useful for a better understanding.

Modeling human structures is extremely difficult because of their complex anatomy. Given the incomplete understanding of the mechanical behaviors of these structures and the uncertainty in the model's ability to describe the physics of the system, it is inevitable that some assumptions will be accepted. It should be considered that the boundary conditions used for bone and biomaterials in FEA, are predetermined average values and the confidence of the analysis depends on the well-defined boundary conditions.

CONCLUSION

Both STU and FEA analysis revealed that the required force for failure of the fixation system was statistically higher in HCCS than in Herbert screw. Within the limits of this experimental study, the findings suggested that biomechanical competency of both SG-HCCSs can be promising in the management of mandibular symphysis fractures with the help of the suitable anatomy of the region. The study may also be helpful for the evaluation and comparison of different fixation systems in virtual environments using FEA, but further clinical studies are needed in this area.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics Approval

This study was carried out in accordance with the principles of the Declaration of Helsinki. The study protocol was reviewed and approved by the Institutional Animal Care and Use Committee of Marmara University (Istanbul, Turkey) with the approval number: 07.2014.mar dated 20.02.2014.

Consent to Participate

The study does not involve human subjects, no informed consent was needed.

Consent to Publish

The study does not contain any individual person's data in any form.

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