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# Evaluation of stress distribution in critical anatomic regions following the Le Fort I osteotomy by three-dimensional finite element analysis

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ABSTRACT

In this study, we aimed to measure the stresses both on the pterygoid plates and the cranial base during the down-fracture and at the time of pterygomaxillary osteotomy by using the finite element analysis method to have an idea about the possible causes of complications. Three different surgical approaches were applied to the obtained models. In the Model 1, Le Fort I cuts without pterygomaxillary separation was applied. In the Model 2, same standard Le Fort I cuts were applied with pterygomaxillary separation. Then both models were subjected to a force of 150 N over the anterior spina nasalis to simulate down-fracture. In the third model, same standard Le Fort I cuts were applied. Following this procedure, a force of 50 N was applied with a sharp osteotome to the pterygomaxillary junction to simulate osteotomy. According to the results of this experimental study, the cranial base stress values decreased during the down-fracture in the Model 2. Moreover, it was found that the force transmitted to the base of the skull is less when the height of the pterygomaxillary osteotome is limited to 1 cm as we applied in Model 3.



## 1. Introduction

Maxillary osteotomy at the Le Fort I (LFI) level was first described by Von Langenbeck in 1859 (Perciaccante and Bays, 2012). In 1867, Cheever applied maxillary down-fracture for the first time in order to remove nasopharyngeal neoplasm (Moloney and Worthington, 1981). Wassmund began to apply the LFI osteotomy for the correction of midface deformities in 1927. In these studies, no osteotomy was performed on the pterygomaxillary region and the maxilla was brought to the desired position with intermaxillary elastic bands postoperatively (Perciaccante and Bays, 2012). In 1934, Axhausen achieved total mobilization of the maxilla in two parts in a patient with cleft lip and palate (Axhausen, 1934). Schuchardt showed that the maxilla could be completely released by separating pterygomaxillary junction and it could be brought to the appropriate position by using elastics in 1942 (Schuchardt, 1942). In the 1960s, Obwegeser made great contributions to the development of the technique through clinical trials and recommended the placement of interposition bone grafts between pterygoid plates and maxilla to provide stabilization (Obwegeser, 1965). Rigid fixation for maxillary osteotomies was defined at the beginning of the 1980's (Bays, 1985). Today, LFI osteotomy is frequently performed in the correction of maxillofacial deformities. With the increase of this practice, vascular and neurological complications have also begun to be reported in the literature and these are still being reported today (Kim et al., 2011; Bouletreau et al., 2012; Hacein-Bey et al., 2013). These complications range from mild to severe and there is no consensus about the reasons of the complications after Le Fort I osteotomy. Many researchers defend that the complications are caused by pterygomaxillary osteotomy (PMO) (Cruz and dos Santos, 2006; Lanigan et al., 1993; Lanigan and Guest, 1993; Precious et al., 1991). However, it has been reported that indirect stresses at the cranial base during a difficult down-fracture can also cause such complications (Lanigan and Loewy, 1995; Hoffman and Islam, 2008; Kim et al., 2011).

One of the possible anatomical structures that may be affected during LFI osteotomy is cavernous sinus (Lanigan and Tubman, 1987; Hes and de Man, 1988). The internal carotid artery lies on the medial wall of the cavernous sinus with the abducens nerve in close proximity. The oculomotor, trochlear, ophthalmic and

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maxillary divisions of the trigeminal nerve are located adjacent to the lateral wall of the cavernous sinus within its dural walls. The abducens nerve is the only nerve free within the sinus itself (Lanigan and Tubman, 1987). Therefore, the abducens nerve is more likely to be affected than the other nerves in sphenoid bone fractures (Hanu-Cernat and Hall, 2009). In addition, a hematoma that may develop into the sphenoid sinus may cause an increase in cavernous sinus pressure, which can also press on other cranial nerves (Kim et al., 2011).

Concerning the mechanism of the formation of cranial nerve complications, multiple reasons can be considered. These include indirect compression or traction affecting the cranial base, direct trauma during PMO and difficult down-fracture (Lanigan et al., 1993). In this study, we aimed to measure the stresses both on the pterygoid plates and the cranial base during the down-fracture and at the time of PMO by using the finite element analysis method to have an idea about the possible causes of complications.

## 2. Material and methods

This study was accomplished by static linear analysis with 3D (three dimensional) finite element stress analysis method. An adult patient's maxilla was scanned with conical beam tomography (ILUMA, Orthocad, CBCT, 3M Imtec, Oklahoma, USA) for the modelling of bone tissues. During the scanning process a total of 601 sections were attained. Volumetric data were then re-established with a 0.2 mm slice thickness. The reconstructed sections were exported in DICOM 3.0 format. The exported sections were imported into 3D-Doctor. 3D-Doctor is software that can reconstruct images obtained by many imaging methods including computerized tomography and magnetic resonance in a computer environment. Changes such as simplification and reformatting can be performed on images reconstructed with the software. Radiographic images were transferred to the 3D-doctor software and the feature of bone tissue was determined according to Hounsfield Values using the "Interactive Segmentation" method. Following the decomposition process, 3D model was created by "3D Complex Render" method and the bone tissue was modelled. The 3D model was transformed into a smooth surface consisting of elements with proper rates through simplification methods in 3D-Doctor software. Thus, modelling of maxillary and skull bones was completed. This model consisted of 397.975 elements and 114,166 nodes.

The arrangement of 3D network structure and making it more homogenous, the creation of 3D solid model and the stress analysis of the finite elements operations were realized using a computer (Intel Xeon® R CPU 3), 3D modelling software (Rhinoceros 4.0, Seattle, USA) and analysis programs (VRMesh Studio, VirtualGrid Inc., Bellevue City, USA and AlgorFempro, ALGOR Inc., Pittsburgh, USA). The model was geometrically formed by VRMesh software and then transferred to AlgorFempro software in stl format for analysis. The stl format is a universal value for 3D modelling programs. Since the coordinate information of the nodes is also stored in stl format, no information is lost during the transfer between programs. After being made compatible with Algor software, it was introduced to the software program that the created model is suitable for maxilla. Additionally, the anatomical study of Cheung et al. (1998) was used for the standardization of posterior maxilla and pterygoid plates. The mechanical properties of cortical and cancellous bones were defined according to the experimental data in a previous study (Vásquez et al., 2001). Young's modulus and Poisson's ratios of the bone structures used in the analysis were listed in Table 1.

Three different surgical approaches were applied to the obtained models. In the first model (Model 1), the surgical procedure for Le Fort I consisted of maxillary bilateral osteotomy from the piriform rim to the pterygoid plate, lateral nasal and septal osteotomy without pterygo-maxillary separation (Fig. 1). In the second model (Model 2), the same standard Le Fort I osteotomy was applied but pterygo-maxillary separation was performed (Fig. 2). Then both models were subjected to a force of 150 N over the anterior spina nasalis to simulate down-fracture (Fig. 3). We used a weighing machine to determine this force. We tried to get the approximate force by pushing our thumbs on the platform of the weighing machine. The maximum principal stresses (PS max), minimum principal stresses (PS min) and von Mises stresses (vMS) that occurred at the cranial base and pterygoid plates were measured when this force was applied for both models. In the third model (Model 3), the same standard Le Fort I osteotomy was applied. Following this procedure, a force of 50 N was applied with a sharp osteotome to the pterygomaxillary junction to simulate osteotomy (Fig. 4). We used a Digital Force Gauge (Shimpo FGN-50B, Japan) to determine this force. We placed a flat head on the top of the device and hit by hammer 5 times try to use a similar force as applied during surgery. We used the approximate mean force value obtained in this study. At the time of this osteotomy, PS max, PS min and vMS that occurred at the cranial base and pterygoid plates were measured.

**Table 1**
Young's modulus and Poisson's ratio for the structures.

| Structure | Young's modulus (Gpa) | Poisson's ratio |
|---|---|---|
| Cortical bone | 13,7 | 0,3 |
| Cancellous bone | 1,37 | 0,3 |
| Suture | 0,069 | 0,45 |

The maximum and minimum principal stresses are the normal stresses in a plane, always perpendicular to each other, and oriented in directions for which the shear stresses are zero. PS max is considered as the most tensile stress while the PS min is regarded as the most compression stress. The vMS were used for this evaluation because of the suitability and the validity of the von Mises theory of failure. The von Mises criterion is a common and well-tested theory of failure practicable to isotropic and ductile materials (Gautam et al., 2007). The von Mises criterion is also known as the maximum distortion energy criterion and it is frequently used to predict the yield of ductile materials. It indicates that failure occurs when the energy of distortion reaches the same energy for yield/failure in uniaxial tension. In addition, the Von Mises criterion provides a reasonable estimate of fatigue failure, particularly for repeated tensile and tensile-shear loading.

## 3. Results

The obtained stress values are given in Table 2.

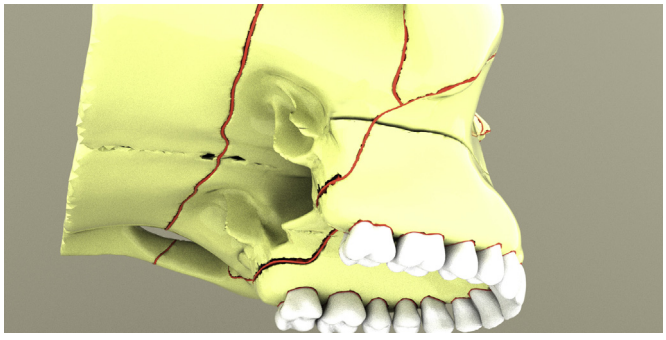

**Fig. 1.** Le Fort I cuts without pterygomaxillary separation was applied in the Model 1.

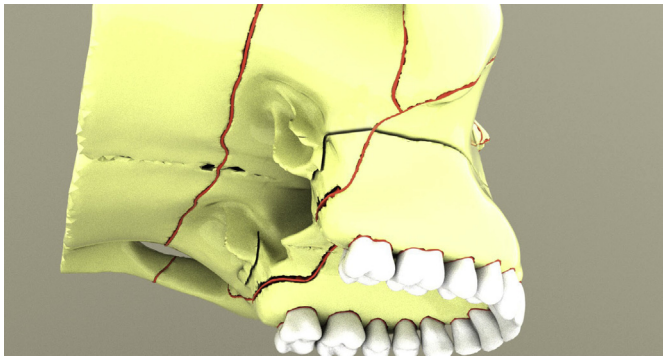

**Fig. 2.** Same standard Le Fort I cuts were applied with pterygomaxillary separation in Model 2.

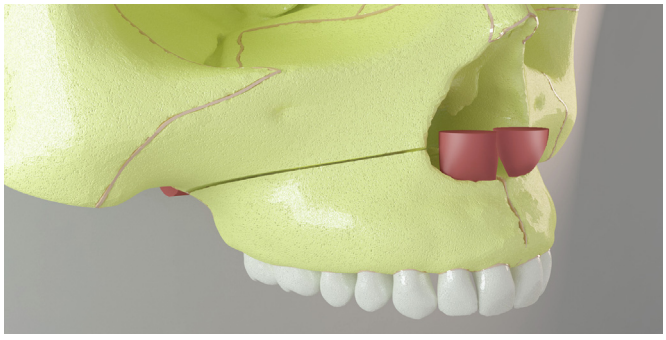

**Fig. 3.** Both models were subjected to a force of 150 N over the anterior spina nasalis to simulate down-fracture.

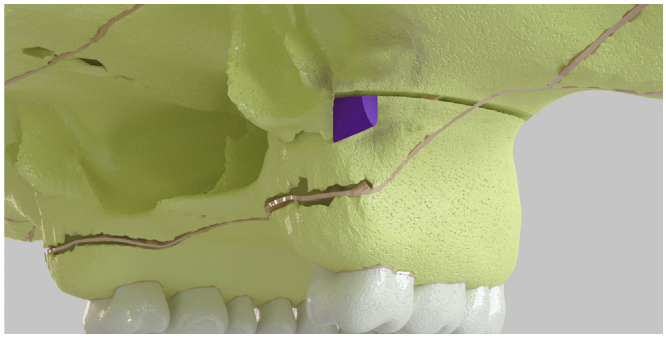

**Fig. 4.** In the third model, same standard Le Fort I cuts were applied. Following this, a force of 50 N was applied with a sharp osteotome to the pterygomaxillary junction to simulate osteotomy.

Lateral pterygoid plate: When Model 1 and Model 2 were compared, a reduction in all stress values was observed in Model 2. Moreover, the obvious reduction in the values of vMS and PS min was striking (Figs. 5 and 6). In Model 3, a remarkable increase in all stress values was observed (Fig. 7).

Medial pterygoid plate: Compared with Model 1and Model 2, along with a decrease in all stress values, a marked decrease in vMS and PS min values was seen in Model 2 (Figs. 5 and 6). In Model 3, along with an increase in all stress values, a marked increase in vMS and PS min values was seen (Fig. 7).

Canalis opticus: When the first and second models were compared, it was noticed that the stress values were decreased in the second model where pterygomaxillary separation is performed (Figs. 8 and 9). In Model 3, it was observed that the stress values measured at this region during the PMO were the lowest (Fig. 10).

Sulcus caroticus: Similar to the canalis opticus region when Model 1 and Model 2 were compared, it is remarkable that vMS and PS max values were decreased in Model 2 (Figs. 8 and 9). In Model 3, the measured vMS and PS max values were found to be minimal (Fig. 10).

Foramen rotundum: It was noted that the vMS and PS max values in this region were decreased in Model 2 (Figs. 8 and 9). In Model 3, it was observed that the stress values measured during the PMO were the lowest (Fig. 10).

## 4. Discussion

LFI osteotomy is one of the most common methods used to correct maxillofacial deformities. Although it has a low complication rate, researchers are still designing specific hand tools to avoid permanent neurological disorders and continue to develop the technique. In addition, both the morbidity and the duration of operation decreased dramatically with the application of hypotensive anesthesia. Some theories about the mechanism of the formation of these complications have been put forward. The transmission of indirect stress and strain (traction, compression and countercoup) or the occurrence of direct trauma (traumatic pterygomaxillary separation and difficult down-fracture) can cause injury to the nerves (Lanigan et al., 1993).

It is seen that neurological complications which may cause serious consequences in the literature are reported for the first time in the early 80s (Watts, 1984). The data on neurological complications following LFI osteotomy are given in Table 3. In general, the most common nerve injury after LFI osteotomy occurs in the oculomotor (III) and abducens (VI) nerves. Many authors have reported that a displaced fracture in the sphenoid bone is the cause of direct cranial nerve injuries (Lanigan et al., 1993; Newlands et al., 2004; Reiner and Willoughby, 1988; Kim et al., 2011). One of the most important causes of this condition is misplacement of the osteotome during PMO. Upward positioning of the osteotome may lead to more stress in the superior orbital fissure area and cranial base, and fractures extending to this region (Lanigan and Guest, 1993; Newlands et al., 2004).

**Table 2**
Stress values in anatomical regions (N/mm$^2$).

| | Stress values that occur during the down-fracture Model 1 (without PMO) | | | Stress values that occur during the down-fracture Model 2 (with PMO) | | | Stress values that occur during the PMO Model 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | sVM | PS max | PS min | sVM | PS max | PS min | sVM | PS max | PS min |
| Lateral pterygoid plate | 0,131176 | 0,031572 | −0,112372 | 0,025946 | 0,018615 | −0,010946 | 0,401964 | 0,220031 | −0,233652 |
| Medial pterygoid plate | 0,274288 | 0,014903 | −0,267796 | 0,013943 | 0,012625 | −0,002578 | 0,238455 | 0,031825 | −0,219678 |
| Canalis opticus | 0,055062 | 0,036103 | −0,026298 | 0,038672 | 0,018920 | −0,025568 | 0,005591 | 0,003115 | −0,008904 |
| Sulcus caroticus | 0,056912 | 0,060811 | −0,002050 | 0,043240 | 0,041578 | −0,003947 | 0,001050 | 0,000684 | −0,000507 |
| Foramen rotundum | 0,180018 | 0,148527 | −0,05330 | 0,179420 | 0,141276 | −0,060955 | 0,013994 | 0,000277 | −0,014671 |

PMO: Pterygomaxillary osteotomy, vMS: von Mises Stress, PS max: Maximum principle stresses, PS min: Minimum principle stresses.

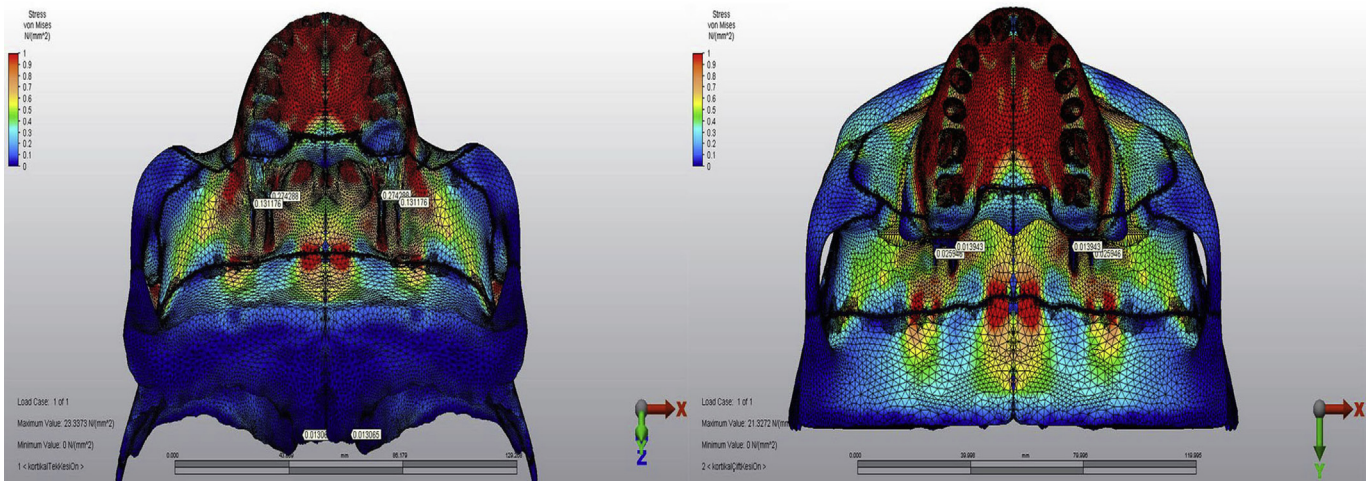

**Fig. 5.** When Model 1 and Model 2 were compared, a reduction in von Mises stresses on the pterygoid plates was observed in Model 2.

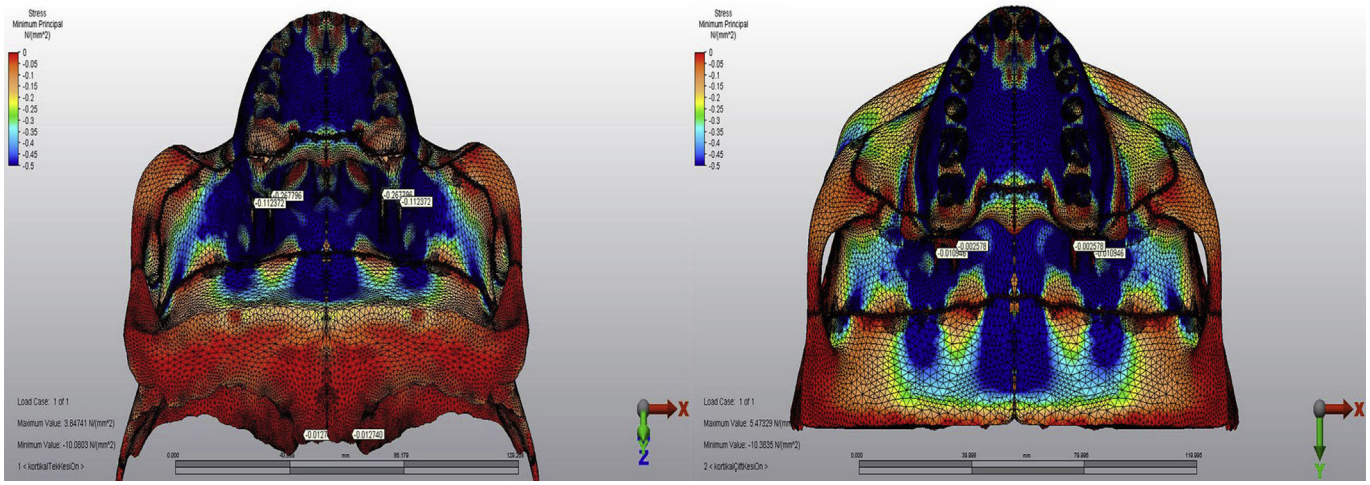

**Fig. 6.** Compared with Model 1and Model 2, a marked decrease in minimum principal stresses on the pterygoid plates was seen in Model 2.

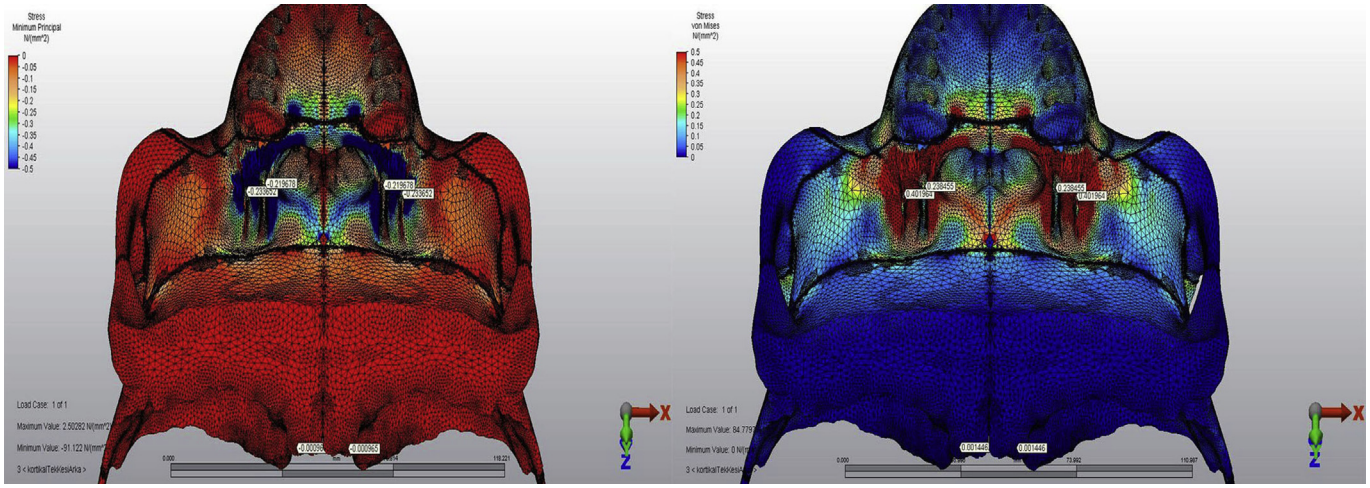

**Fig. 7.** A remarkable increase in von Mises and minimum principal stresses was found on the pterygoid plates during pterygomaxillary osteotomy.

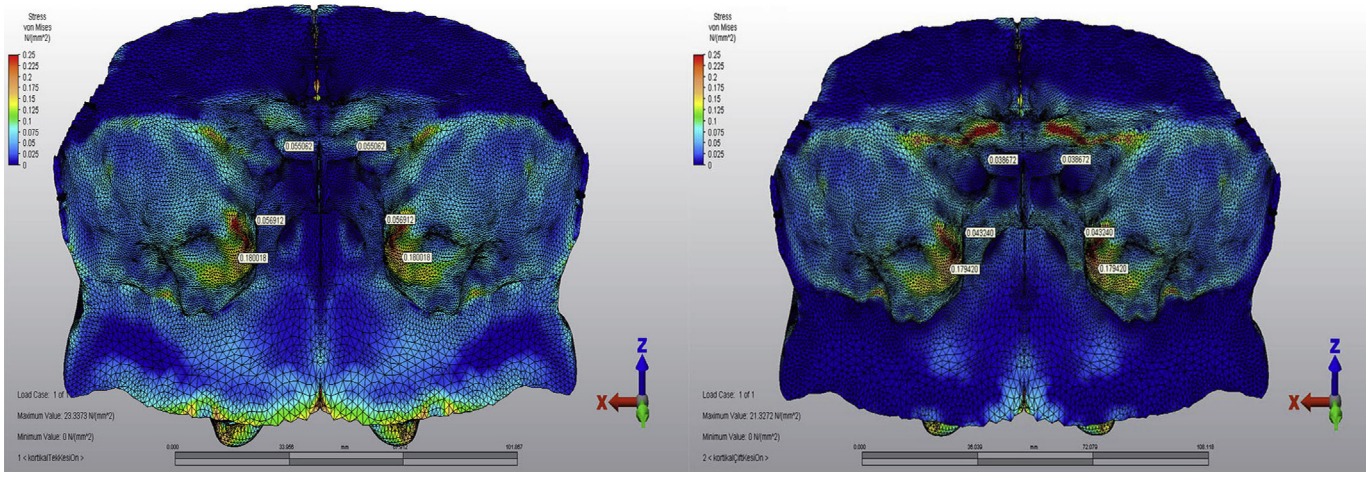


**Fig. 8.** Compared with Model 1 and Model 2, it was found that the von Mises stresses were decreased on the cranial base in the second model where pterygomaxillary separation is performed.

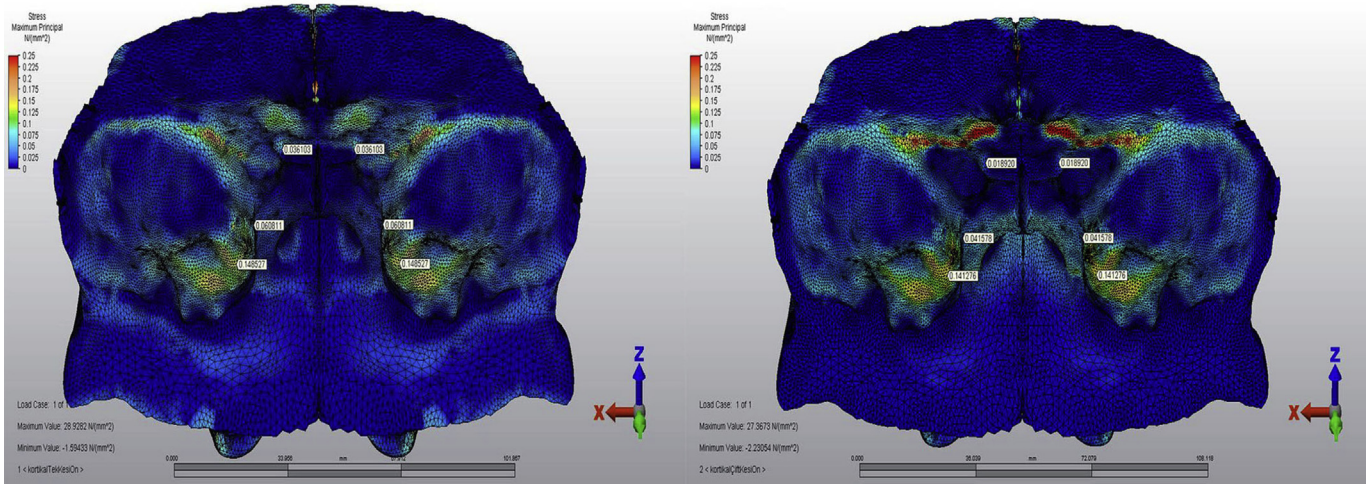


**Fig. 9.** Compared with Model 1 and Model 2, it was noted that the maximum principal stresses were decreased on the cranial base in the Model 2 where pterygomaxillary separation is performed.

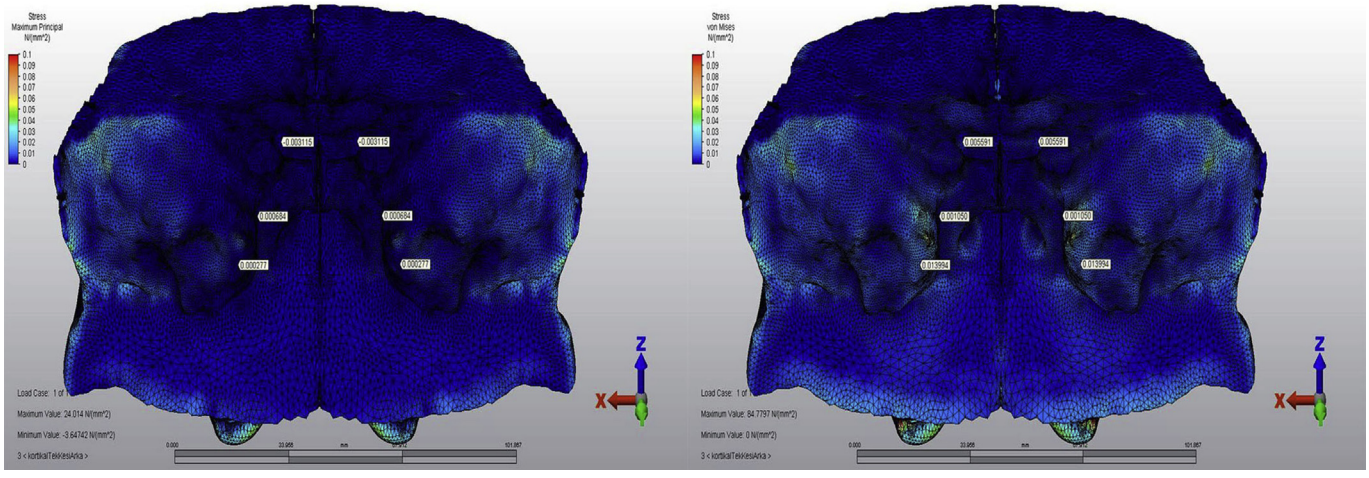


**Fig. 10.** In Model 3, it was observed that the von Mises and maximum principal stresses on the cranial base were the lowest.

**Table 3**
The published neurological complication data following LFI osteotomy up to now.

| Author & Year | Age/Gender | Injured nerve | Recovery |
|---|---|---|---|
| Watts, 1984 | 18/F | Abducens | 7 weeks |
| Carr and Gilbert, 1986 | 17/M CLP | Partial oculomotor | 8 weeks |
| Reiner and Willoughby, 1988 | 27/F | Abducens | 5 months |
| Lanigan et al, 1993 | 33/F | Partial oculomotor | 5 days |
| | 17/F | Optic | No recovery |
| | | Optic | Partial recovery |
| Bendor-Samuel et al, 1995 | 14/M CLP | Oculomotor | Partial recovery |
| | 30/M CLP | Bilateral abducens | 12 months |
| | | Optic | Light perception |
| Herold and Falworth, 1996 | 35/M | Pupil sparing oculomotor | 6 weeks |
| Girotto et al, 1998 | 21/M | Optic | Light perception |
| | UD/M CLP | Optic | No recovery |
| Wilson et al, 2000 | 20/M | Optic | Light perception |
| Lo et al, 2002 | 12/F CLP | Optic | Light perception |
| | 12/M CLP | Optic | No recovery |
| Newlands et al, 2004 | 33/F | Pupil sparing oculomotor | 1 weeks |
| | | Abducens | 10 weeks |
| Cruz and dos Santos, 2006 | 22/F | Optic | No recovery |
| Cheng et al, 2007 | 18/M | Optic | Partial recovery |
| Hanu-Cernat and Hall, 2009 | 16/F | Abducens | 6 weeks |
| Chrcanovic and Custodio, 2011 | 28/F | Oculomotor-Abducens | 5 days |
| | | Optic | Partial recovery |
| Kim et al, 2011 | 19/M CLP | Abducens | 5 months |
| | | Ophthalmic | 2 months |
| | | Maxillary | 2 months |
| | | Partial damage of Optic | 6 months |
| Hacein-Bey et al, 2013 | 18/M | Vagus | 1 year |
| | | Accessory nerves | |
| Rodriguez-Navarro and Gonzalez-Valverde, 2018 | 41/F | Optic | UD |

F: Female, M: Male, CLP: Cleft lip and palate, UD: Undeclared.

III. and VI. Cranial nerves continue anteriorly along the cavernous sinus and enter with a common tendon into the orbit through superior orbital fissure. The oculomotor nerve, which contains somatic motor fibers, is divided into superior and inferior segments. The superior part moves the superior rectus and lateral palpebrae superioris muscles while the inferior part moves the medial rectus, inferior rectus and inferior oblique muscles (Newlands et al., 2004). Pupil-sparing oculomotor nerve paralysis occurs when only the upper part of the nerve is affected. Thus, ptosis and upper-view paralysis occur. The sixth nerve is one of the most common cranial nerve injuries because of its long intracranial path. This nerve also contains somatic motor fibers and travels along the cavernous sinus near the sphenoid sinus wall and enters the superior orbital fissure to activate the lateral rectus muscle. The nerve is most affected in the fractures of the sphenoid sinus wall (Kim et al., 2011). When it is affected, the patient cannot move his or her eye to the lateral direction. Indirect injuries caused by force applied during PMO can lead to arterial ischemia for the cranial nerves. Fractures of the skull base may cause cavernous sinus thrombosis or carotid-cavernous sinus fistula, leading to permanent cranial nerve damage (Bendor-Samuel et al., 1995; Kim et al., 2011). Complete oculomotor nerve palsy occurs with a blockage of the artery around the cranial nerve. In such a case, ischemic lesions are seen in diabetic ophthalmoplegia. Therefore, forces that are transmitted to the cranial base during osteotomy or the hematoma/edema that forms on the cranial base may cause cranial nerve palsy by causing an arterial ischemia around the nerve (Chrcanovic and Custódio, 2011). If the cause is hematoma or edema, paralysis will also recede when this condition is reduced. Apart from these cranial nerves, cases of optic nerve injury resulting in loss of vision after LFI osteotomy have also been reported (Lanigan et al., 1993; Bendor-Samuel et al., 1995; Girotto et al., 1998; Cruz and dos Santos, 2006; Chrcanovic and Custódio, 2011). In all of these cases, it is noteworthy that direct injuries caused by bone fragments extending into the optical channel are observed. The authors reported that this condition originated from high-level pterygoid plate fractures reaching the base of the skull during PMO. Unfortunately, none of the cases with optic nerve damage showed total improvement.

Although LFI osteotomy is frequently performed nowadays, there is no clear consensus regarding PMO application during this procedure. It is well established that complications are caused by unwanted fractures of the pterygoid plates that are applied during PMO and that these fractures lead to direct or indirect injuries to the cranial nerves (Carr and Gilbert, 1986; Herold and Falworth, 1996; Newlands et al., 2004; Cruz and dos Santos, 2006; Kim et al., 2011; Chrcanovic and Custódio, 2011). Therefore, a group of clinicians recommended down-fracture without using an osteotome for pterygomaxillary separation (Precious et al., 1991; Precious et al., 1993; Breeze et al., 2016). Precious et al. (1991) reported that more than 500 patients underwent LFI osteotomy without PMO and did not encounter any serious complications. Again, Precious et al. (1993) performed pterygomaxillary separation with a chisel in 30 patients and without a chisel in 28 patients and they studied early postoperative CT outcomes of patients. The authors reported that acceptable separation between the maxilla and the pterygoid process took place in 80% of the cases in which a chisel was used and in 86% of those in which a chisel was not used. They stated that no fracture was noted in the upper third of the pterygoid plates, and there was no evidence of fracture of the cranial base in either group. Recently, Breeze et al. (2016) performed LFI surgery in 138 patients without PMO and reported that they did not encounter any serious complications except epistaxis.

In this study, a force of 150 N was applied from the anterior maxilla to mimic down-fracture in Model 1 and 2. According to the obtained results, when the down-fracture is performed without PMO, the PS min and vMS values of the medial pterygoid plate increase. Earlier experimental studies have also reported higher stress values in medial pterygoid plates (Hiranuma et al., 1988; Ozdemir et al., 2017). If this situation is clinically evaluated, it can

be considered that the possibility of fracture especially in the medial pterygoid plate may be higher because the compression force is increased in the medial pterygoid plate during the down-fracture in cases without PMO. Some authors reported fractures in the pterygoid plates during down-fracture in cases where PMO was not applied, but these fractures were reported at a low level (Precious et al., 1991; Precious et al., 1993; Breeze et al., 2016).

According to the results of this experimental study using three-dimensional finite element analysis, the cranial base stress values decreased during the down-fracture in the PMO applied model (Model 2). When clinically evaluated, it can be considered that the pterygomaxillary separation reduces the stress on the cranial base and may reduce the indirect injuries that may occur in this region. However, in Model 3, high values of PS min values (compression) were found in the pterygoid plates during PMO, whereas PS max values (tension) on the cranial base were found to be at least level. In other words, it is seen that the amount of force transmitted to the base of the skull is not large when a high amount of compression force is generated in the pterygoid plates during PMO. Clinically, these results suggest that high stress values in the pterygoid region during PMO may create high-level fractures extending to the base of the skull in the pterygoid plates when the osteotome is not correctly positioned. In this study, it was found that the force transmitted to the base of the skull is less when the height of the pterygomaxillary osteotome is limited to 1 cm as we applied in Model-3. Therefore, if PMO is to be administered, the height of the osteotomy can be limited to 1 cm to minimize complications.

Considering that PMO was performed in all presented case reports of complications in the literature, an increased number of down-fractured cases without PMO in the clinic may give us a clearer idea of whether the rates of neurological complications have changed in particular. In addition, limiting the height of the PMO to 1 cm results in the reduction of the stresses on the skull base. In this study, a force was applied over the lateral pterygoid plate to mimic PMO. However, as the osteotomy progresses towards the medial pterygoid plate, there is a need for further studies to determine whether the stress values at the base of the skull have changed.

## 5. Conclusion

The tension forces on the cranial base decreased during the down-fracture in the PMO applied model. In addition, although the amount of stress naturally increases in the pterygoid plates during osteotomy in model 3, when the height of the pterygomaxillary osteotomy is limited to 1 cm, the amount of stress on the cranial base decreases.

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## Conflicts of interest

The authors declare that there are no conflicts of interest.

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