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Research Article

Evaluation of Stability and Stress Distribution on Plate and Bone for Correction of Anterior Open Bite with Le Fort I Osteotomy: New Plate Design

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Abstract

Aim: Many different fixation methods have been proposed in the literature for the treatment of open bite. Beginning with the use of plates and screws, rigid fixation methods have become commonplace, however, open bite is a disorder prone to relapse despite rigid fixation. In our study, we aimed to eliminate the need for guided split usage during surgery and to increase postoperative stabilization in open bite patients with a new personalized plate design.
Material and Method: For this purpose, a three-dimensional (3D) head model was created in the virtual environment. After the Le Fort I osteotomy on the model, the inferior segment of the maxilla was placed 1 cm forward and positioned to leave a space between the inferior and superior part of the maxilla. Different fixation methods were applied to fix the bone segments. In the first group, four plates with a thickness of 0.8 mm were fixed. In the other groups, we used three different thicknesses (0.4 mm, 0.6 mm, 0.8 mm) of the continuous plate we designed. The amount of movement and tension that occurred on the bone segments, plates, and screws were evaluated.
Results: The maximum movement in the study was observed with the standard 4-plate fixation method, and the minimum movement was observed with the custom plate system with 11-screw type with a thickness of 0.8 mm. As a result, it has been found that the custom-made continuous plates provide a more rigid fixation than the standard plates.
Conclusion: It may be possible to reduce the likelihood of a relapse problem by designing a plate with the appropriate thickness and form to spread the stress on the bone over a wider area.

Keywords: Orthognathic surgery, bone fixation, Le Fort I osteotomy

INTRODUCTION

Anterior open bite (AOB) is defined as non-contact between maxillary and mandibular anterior teeth (1). The incidence of AOB in the community ranges from 1.5% to 11%, and this ratio varies between races (2). The difficulty in the treatment of patients with anterior open bite closure is due to the fact that the etiology of the problem is multifactorial (skeletal, dental, soft tissue, bad habits, etc.) (3). Several studies have reported a tendency for relapse after conventional or surgical orthodontic treatment for this purpose (4). For this reason, it is considered one of the dentofacial deformities that are difficult to treat due to the difficulties of determining the etiology and the possibility of relapse after treatment.

The Le Fort I osteotomy became popular in the 1970s, and it has increasingly been used for correcting anterior open bite. This method allows the treatment of upper jaw hypoplasias that are in three planes. Recent studies have focused on the safety of maxillary movements in relation to long-term stability and relapse (5,6).

There are differences in the rates of relapses in the literature as the anomalies in different etiologies can be corrected by Le Fort I osteotomy. Dowling et al. identified only 14% of patients with clinically significant relapses (>2 mm) without a result, additional operations, or associated syndromes (7). In 1991, Proffit et al. reported a similar rate of recurrence (>2 mm) in the study they published (8). Additionally, rates of relapse in patients treated for vertical excesses are also similar (9,10). Studies have reported that relapse rates are between 0-18% for the anterior maxilla and 6-7% for the posterior maxilla when the maxilla is positioned in the superior position. Relapse rates for advancing the maxilla range from 5-15%. They

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reported that maxillaries positioned inferiorly (using bone grafts) could result in up to 28% of cases of anterior region relapse and up to 70% of posterior relapse (11). It has been reported that most of the relapses in open bite cases occurred during the first 6 months, and the amount of movement was the primary cause of relapse (7). After the correction of maxillary anterior open bite, the relapse rates in the sagittal direction increase to 37%, while the vertical relapse rates are as high as 65% of the total movement (12).

Preoperative planning is essential for the success of orthognathic procedures. In recent years, with the development of technology, preoperative planning - in addition to traditional methods - can be done by computer, and post-op results can be seen before the operation. Also, customized surgical guides or fixation plaques can be made using Computer-aided design/ Computeraided manufactur-ing (CAD/CAM) systems. In orthognathic surgery, the soft tissues are stretched due to the movement of the jaws. Existing lengths of muscle fibers and occlusal forces lead to relapse formation after postoperative functions. Studies in the literature indicate that the odds of relapse are increased by the amount of movement of the maxilla. The key factors that influence the relapses are fixation technique and resistance of the fixation material to occlusion forces. Relapse in anterior open bite patients is the most important problem because of the amount of movement made after the osteotomy. In our study, it is aimed to increase the rigid fixation stabilization and increase the resistance to occlusion forces by increasing the plate surface. In addition, it is thought that, in addition to the result obtained, added value can be achieved by shortening the operation time with preoperative digital adaptation.

To evaluate the stabilization, conventional 4-hole titanium plates, and a designed titanium plaque are modeled virtually. It is planned to compare the plaques in terms of stabilization and durability against occlusal forces (in the bone/plaque connection region) with the finite element analysis method and to evaluate the ideal plate/screw combination and the position where more successful retention is achieved.

MATERIAL AND METHOD

In our study, a new surgical plate design (Figure 1A) was developed to enhance stability when positioning the maxilla anteriorly and inferiorly. We evaluated the results obtained by comparing this designed plate with the conventional 4-plate fixation technique (Figure 1B). Our research employed static, linear analysis using the 3-dimensional finite element stress analysis method to ensure that comparisons were conducted under identical conditions.

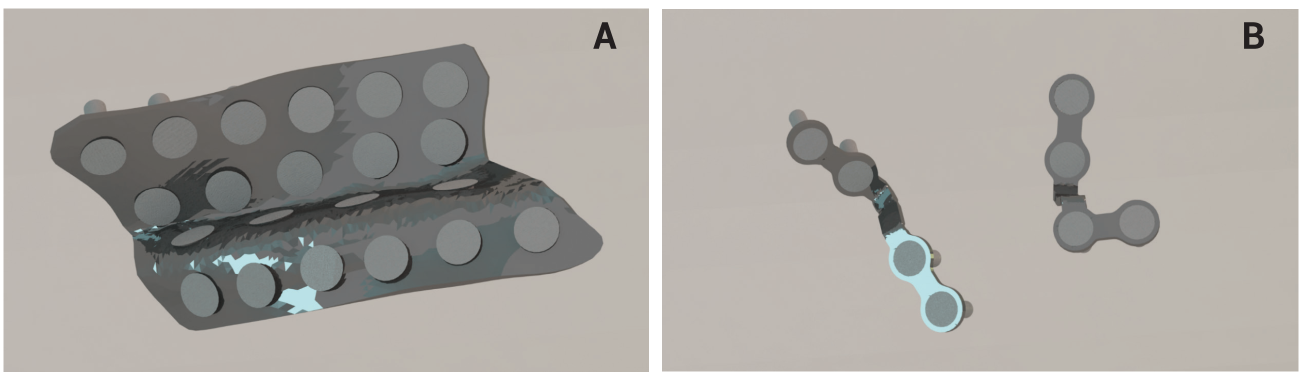


Figure 1. A. New le fort I plate design; **B.** 4 holes miniplate

Using the finite element analysis method, we simulated Le Fort I osteotomy in a three-dimensional (3D) skull model and separated the bone segments. The inferior segment was positioned 1 cm anteriorly and 6 mm inferiorly, with gap left between the segments. 120 Newton (N) force was applied with 60°to the Frankfurt horizontal plane on one side.

The plates we designed were intended to be continuous pieces extending from the zygomatic protrusion to the piriform area. These plates were manufactured in three different thicknesses: 0.4 mm, 0.6 mm, and 0.8 mm, constructed to match the patient's bone shape. During simulation, fixation was achieved using either 8 or 11 screws strategically placed through predefined screw holes on the plate. The objective was to compare both the thickness of the plate and the stabilizing effect of the number of screws used in plate fixation.

To ensure consistency, the locations of the screw holes on the plate were determined based on distances in the standard plate system. In alignment with the anatomical structure of the sampled patient, 11 screw holes were incorporated into the plate, aligning with the bone volume. This approach aimed to provide a comprehensive analysis of the impact of plate thickness and screw quantity on overall stability and performance in the simulated 3D network structure.

The workstation utilized for the 3-D network configuration, homogenization, 3-D solid model creation, and stress analysis in our study featured an Intel Xeon® R CPU 3.30 GHz processor, a 500 GB Hard Drive, 14 GB RAM, and Windows 7 Ultimate operating system. The software tools employed included Rhinoceros 4.0 (Robert McNell&Associates, USA) for 3D solid model creation and stress analysis, an optical scanner with a Version Service Pack 1 operating system, Activity 880 modeling software by smart optics Sensortechnik GmbH, VRMesh Studio by VirtualGrid Inc (USA), and Algor Fempro analysis program (ALGOR, Inc. USA).

Simulation

In our study, a stepped Le Fort I osteotomy was performed. With Le Fort I osteotomy, the anterior descent of the maxilla was placed 1 cm forward, leaving a 6 mm space between the bone segments, modeled as one of the orthognathic procedures with the most relapse. The inferior segment was positioned 1 cm anteriorly with a 6 mm gap between the superior segment. The simulation was conducted in 7 different ways:

- **Model 1:** 0.8 mm thick, 4 holes with 4 plates (8 screws),
- **Model 2a:** Fixed with 2 plates with 17 holes of 0.8 mm thickness (11 screws),
- **Model 2b:** Fixed with 2 plates of 17 holes with 0.8 mm thickness (8 screws),
- **Model 3a:** Fixed with 2 plates of 17 holes with 0.6 mm thickness (11 screws),
- **Model 3b:** Fixed with 2 plates with 17 holes of 0.6 mm thickness (8 screws),
- **Model 4a:** Fixed with 2 plates with 17 holes of 0.4 mm thickness (11 screws),
- **Model 4b:** Fixed with 0,4 mm thick 17 holes with 2 plates (8 screws).

RESULTS

Demographic and clinical data of the groups are shown in the least movement after the chewing force was applied to the model was observed in Model 2a. The maximum movement was determined in the standard Model 1 (Figure 2A).

The amount of movement observed in the X plane after applying the force to the model follows the sequence: Model 1 > Model 4b > Model 4a > Model 3b > Model 3a > Model 2b > Model 2a. There was no significant difference between the models, but most movements were observed in Model 1.

The motion of the Y plane followed a similar trend: Model 1 > Model 4b > Model 4a > Model 3b > Model 3a > Model 2b > Model 2a. Model 2a (Figure 3A) provided the most stable result with a move-ment of 0.438367 mm.

The minimum movement in the Z plane was observed in Model 2a (Figure 3B). The movement amounts of all models were significant, with Model 1 having the highest movement.

The total amount of movement was the highest in Model 1 with a total movement of 6.22 mm (Figure 2B). The minimum movement was determined in Model 2a (11 screws) with 0.6875734 mm (Figure 3B). The order of all models was Model 1 > Model 4b > Model 4a > Model 3b > Model 3a > Model 2b > Model 2a (Graph 1).

Stress analysis revealed that stress occurring in Model 1 is six times higher than the stress in Model 2 (Graph 2). In our custom-designed plates, the maximum stress, at a thickness of 0.4 mm, was observed in Model 4b, fixed with 8 screws. However, even the stress in Model 4b is only one-third of the stress in the standard 4-plate fixation technique (Model 1). Fixation of plates with the same thickness but a different number of screws has minimal impact on the stress on the plate.

Stresses in the screws are notably higher in Model 1 compared to other models. The stress distribution occurs in the same order in both the screws and the plates, and the resulting stresses can be listed as Model 1 > Model 4b > Model 4a > Model 3b > Model 3a > Model 2b > Model 2a. Moreover, the increase in the number of screws leads to a reduction in the stress on the screws (Figure 4A, Figure 4B).

When considering stresses on the bone, the greatest stress is found in Model 1. These stresses are listed in descending order as follows: Model 1 > Model 2b > Model 4b > Model 3b > Model 2a > Model 3a > Model 4a (Graph 3). Examining stresses in the bone, an increase in the number of screws results in a more balanced outcome in terms of strength distribution. Models with 11 screws are less desirable than those with 8 screws. Among the 8-threaded models, Model 3 with a thickness of 0.6 mm exhibited the least stress (Figure 5A, Figure 5B).

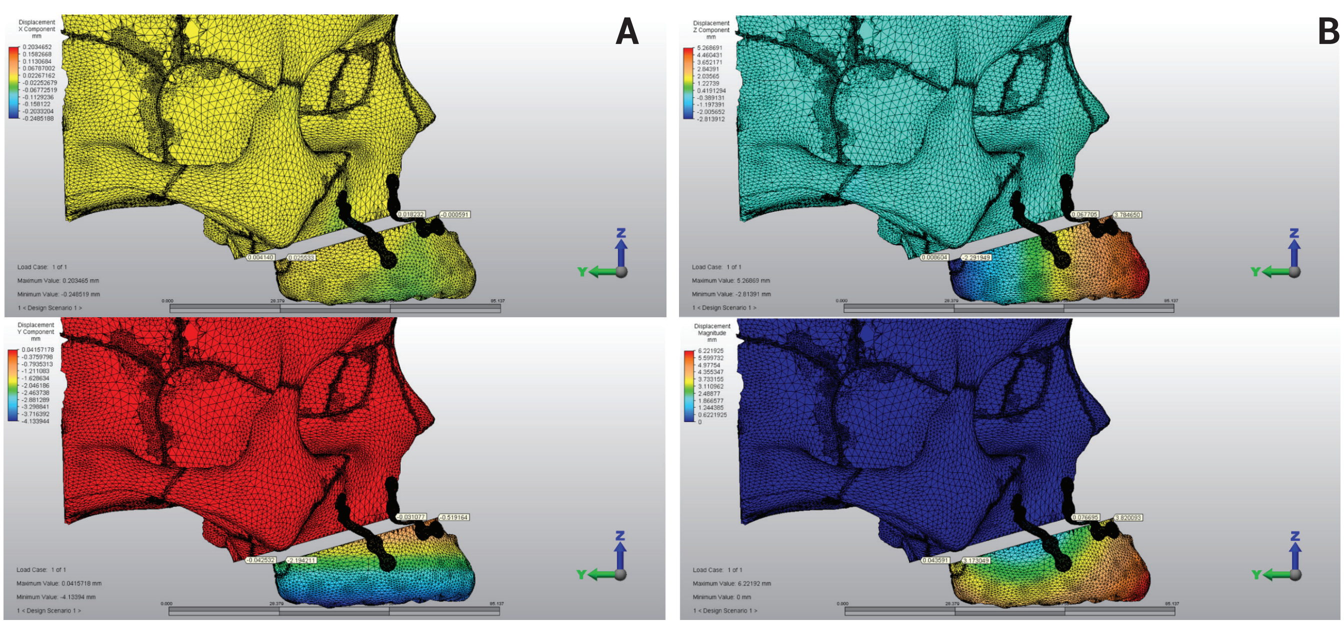


Figure 2. A. Evaluation of movement after force applied; **B.** Evaluation of movement after force applied

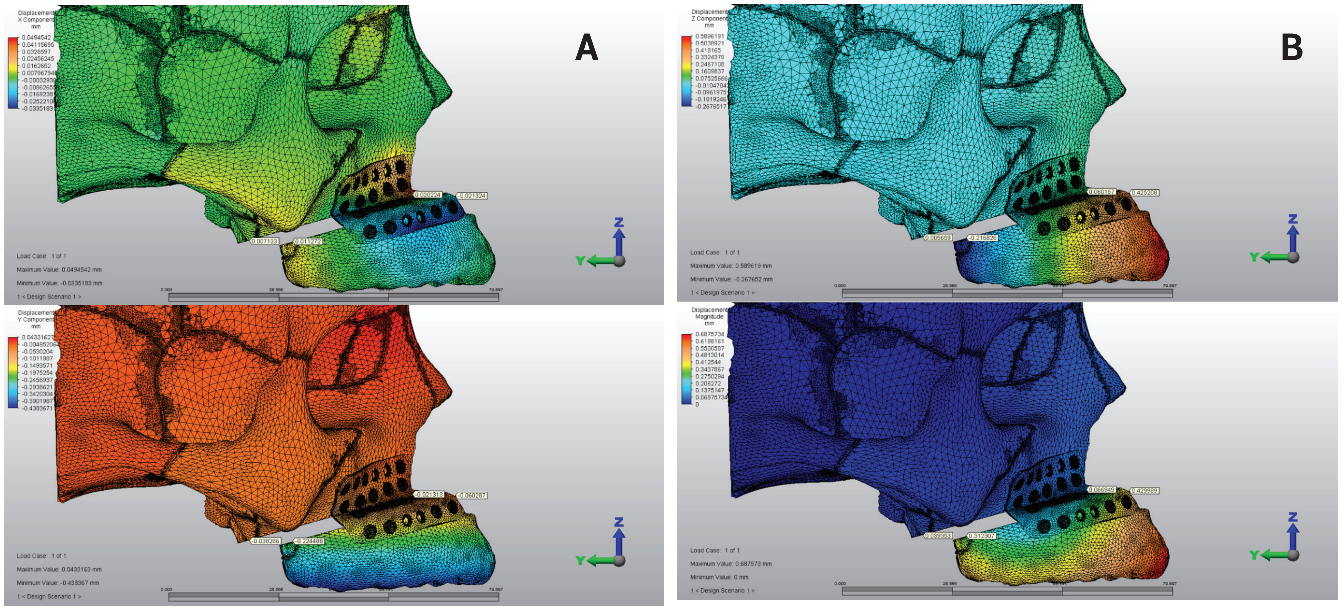


Figure 3. A. Evaluation of movement after force applied with design plate; **B.** Evaluation of movement after force applied with design plate

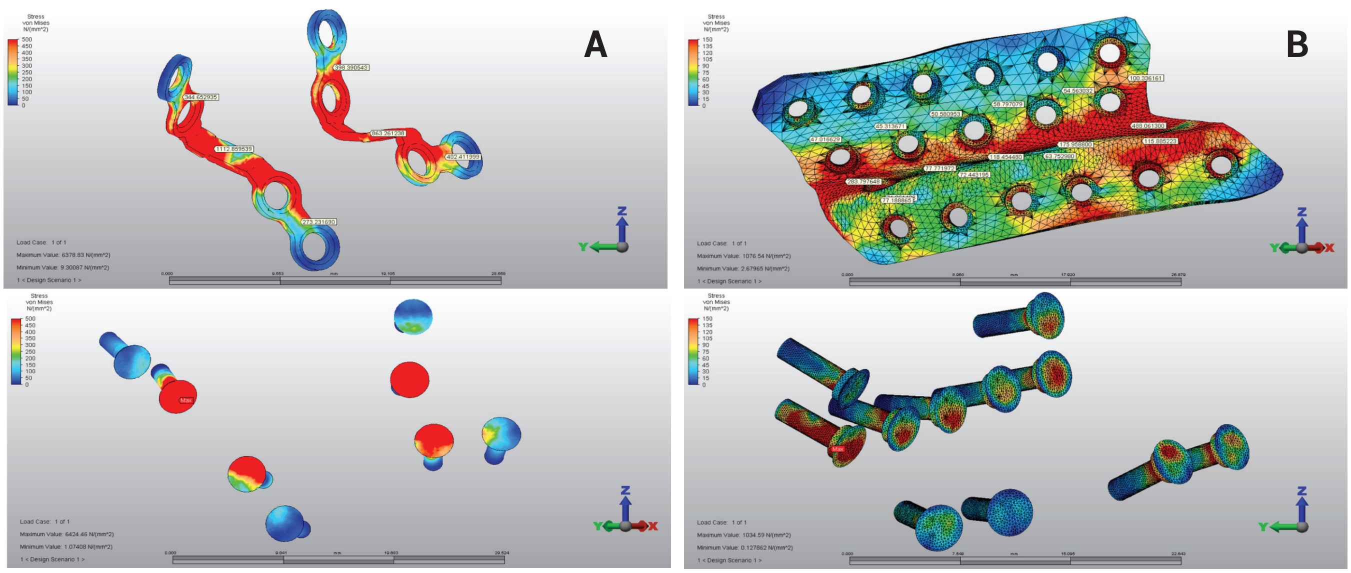


Figure 4. A. Stress distribution on plate and screw; **B.** Stress distribution on design plate and screws

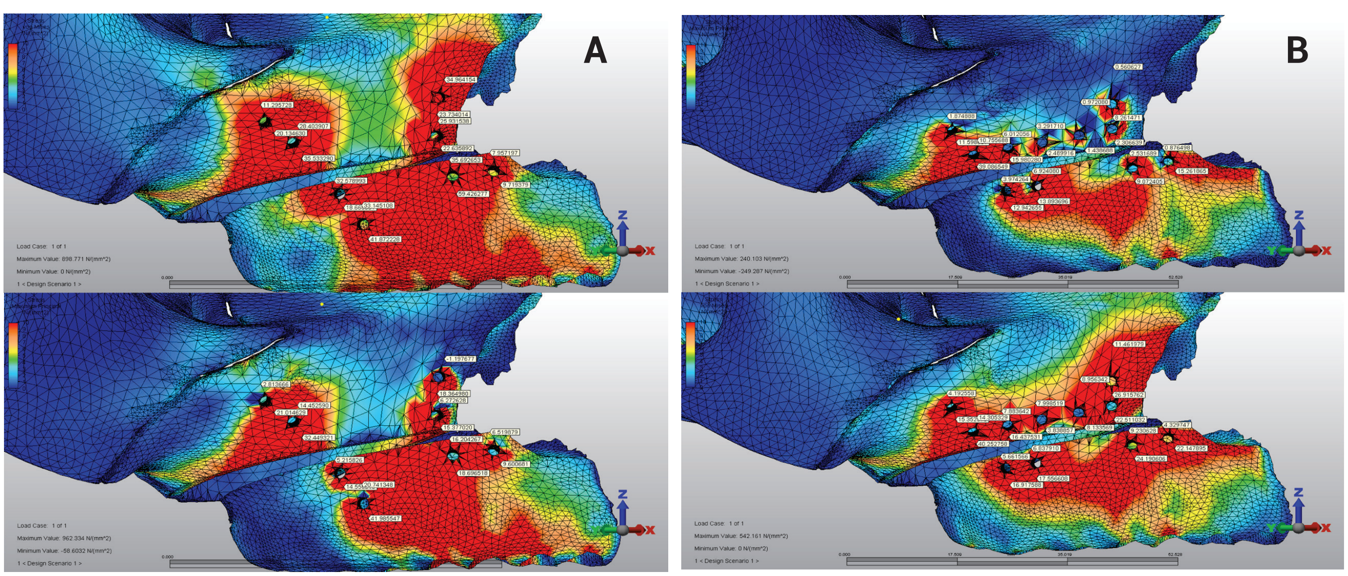
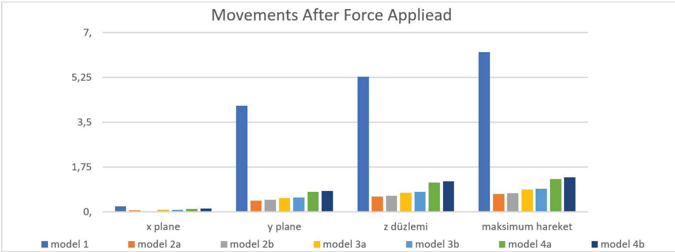
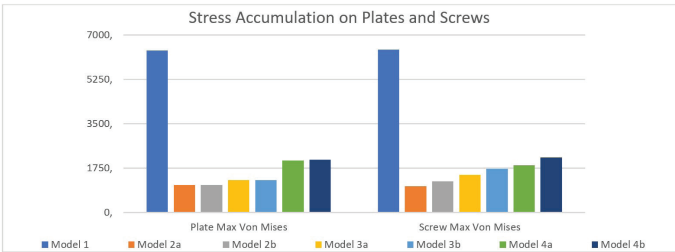


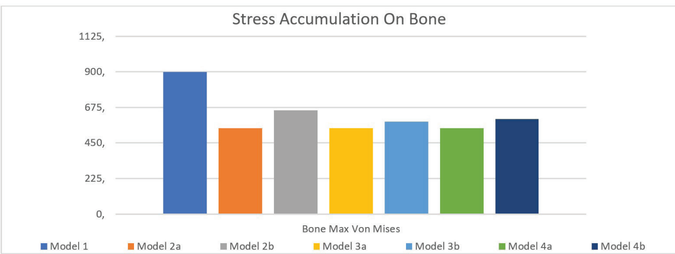
Figure 5. A. Stress distribution on bone; **B.** Stress distribution on bone with design plate



Graph 1. Movements at all plane



Graph 2. Stress accumulation on screws and plates



Graph 3. Stress accumulation on bone

DISCUSSION

The primary objective of Le Fort I surgery is to maintain the stability of the inferior segment in its new position after the separation of the superior and inferior segments.

There are differences in the rates of relapses in the literature as the anomalies in different etiologies can be corrected by Le Fort I osteotomy. Dowling et al. identified only 14% of patients with clinically significant relapses (>2 mm) without a result, additional operations, or associated syndromes (7). In 1991, Proffit et al. reported a similar rate of recurrence (>2 mm) in the study they published (8). Additionally, rates of relapse in patients treated for vertical excesses are also similar (9,10). Studies have reported that relapse rates are between 0-18% for the anterior maxilla and 6-7% for the posterior maxilla when the maxilla is positioned in the superior position. Relapse rates for advancing the maxilla range from 5-15%. They reported that maxillaries positioned inferiorly (using bone grafts) could result in up to 28% of cases of anterior region relapse and up to 70% of posterior relapse (11). It has been reported that most of the relapses in open bite cases occurred during the first 6 months, and the amount of movement was the primary cause of relapse (7). After the correction of maxillary anterior open bite, the relapse rates in the sagittal direction increase to 37%, while the vertical relapse rates are as high as 65% of the total movement (12).

Moldez et al. (2000) concluded that, in their study, Class III AOB patients who underwent bimaxillary surgery experienced 8.7 relapses at a 5-year follow-up. Additionally, for patients rotating clockwise in the palatal plane, the study reported that the inferior orientation of the anterior maxillary segment was more stable than for those undergoing frontal opening correction (13).

Espeland et al. (2008) reported negative overbite in 12 patients after a 3 year follow-up. This occurred with standard single-piece Le Fort I interstitials and fixation utilizing 2 L-shaped 1 mm thick miniplates for 2 sherds on each side (14).

Various studies have indicated that stabilization is compromised when the maxilla is positioned inferiorly with Le Fort I osteotomy in Class III AOB cases, leading to a gap between the inferior and superior segments (15-18).

The study of tissue and organs during the consideration of operative techniques, such as maxillary Le Fort I osteotomy and fixation, is particularly challenging due to ethical problems, difficulty of standardization and insufficiencies in measurement and analysis. Finite Element Analysis (FEA) effectively addresses these challenges, allowing for detailed mathematical study of complex numerical values such as displacement, stress, and compressive stresses caused by forces acting on structures with complex geometry. Transferring the structures to be examined with FEA to the computer ensures that stress values arising after force application are obtained pricesly. The complex calculations of FEA transform the studied model into a series of simple equations (19-22).

Nagasao et al. first utilized FEA in 2007 to demonstrate the relationship between the diameter and stability of fixation screws in Le Fort I osteotomy. They reported that stabilization was greater when the thickness of the fixation site bone equaled the size of the fixation screw (23).

In their study Atac et al. employed Le Fort I osteotomy in 2008 and 2009, using 4-hole plain plaques in the aperture priform rim area and posterior zygomatic support points in a study comparing 2 and 4 plate fixations with FEA after different maxillary postures. They reported that plaque fixation was less stressful than the 2-system (24, 25). In one of their studies, using Le Fort I osteotomy, 5 mm advancement in the upper cannula, 4 mm inferior positioning, and bone grafting to the gap between bone segments were performed (26). The plaques used were 2 mm thick, unlike our study. Comparison revealed that the data obtained indicated less stress on the plaque in the 4-plaque fixation than in our study. This difference may be attributed to the fact that in our study, both the inferior and anterior movements were greater, while the plaque thickness was less. It can be said that stability changes linearly with plate thickness, inversely proportional to the amount of movement.

Coşkunses et al. (2015) used FEA to evaluate Le Fort I osteotomy, employing mini-plates pre-bent for fixation in models. Pre-bent plates proved a good alternative to conventional two-plate systems for advances up to 5 mm, but their predictability and feasibility in advances greater than 5 mm and in vertical position changes require further study (27).

Huang et al. (2016) investigated the biomechanical relations of different mini plate fixations in models made maxillary using Le Fort I osteotomy by FEA. They reported that more stable results were obtained with lateral fixation using L-shaped plaques, and maximal 5 mm advancements in the maxilla would increase plaque breakage and relapse risk (28).

To achieve desired aesthetic and functional results after orthognathic surgery, correct repositioning of the upper jaw is crucial. The method for 3D control of upper jaw movements during surgery is still controversial (29,30). Traditionally, the upper jaw is repositioned using surgical splints based on intraoral or extraoral measurements. There is a high probability of errors in such measurements, with splints typically prepared manually before surgery using surgical models. Errors of up to 5 mm in the upper jaw position have been reported after surgery according to preoperative planning (31).

During orthognathic surgery, when the upper jaw moves, only the mandible can be used as a reference point to determine the new position of the maxilla. To position the maxilla correctly, the mandible to which the surgical splint is inserted is directed to the top and back positions of the joint pit. However, during surgery, there is no anatomical point or chewing gauge to guide the placement of the mandible, other than the surgeon's experience. Additionally, an average of 2.4 mm of vertical movement of the condyle was reported in the patient under anesthesia in the supine position. Consequently, the mandible may have been directed farther than necessary, leading to incorrect mandibular posterior mandibular and causing the maxillary segment to move forward in the anteroposterior direction and rotate counterclockwise according to the preoperative plan (32).

Suojanen et al. (2016) conducted a study to evaluate the accuracy of personalized cutting guide and fixation plates in orthognathic procedures without using of surgical splints. They included 32 patients and Le Fort I osteotomy planned for all cases. In all cases, except one, the surgical application was done as planned. In one patient, the designed plaques did not conform to the bum, suggesting that this may be due to an incorrect design of the posterior osteotomy, possibly due to misdetection of the lower jaw position during computed tomography (33).

In a study focused on patients with Class III open bite, fixation was achieved by positioning the using upper jaw segment 6 mm inferiorly for 10 mm advancement and open-closing correction. The evaluation of plaque stability in vertical movements by leaving a gap between the bone segments was also a targeted aspect.

When designing a single-piece plaque, our goal was to enhance stabilization, considering the following points:

- Achieve minimum plate thickness,
- Ensure that the plaque is lightweight,
- Facilitate fixation (screws can be applied to each zone).

In our study, the plates were designed with 6 different thicknesses (0.4 mm, 0.6 mm, 0.8 mm) and numbers of screws (8 or 11). To reduce the weight of the designed plates, 17 screw holes were formed in the direction of the patient's anatomy on each plate by placing a screw hole in the appropriate range on the entire surface. This approach aimed to prevent the plaque from becoming unusable by allowing fixation through the appropriate hole at the end flap and to address possible complications during the operation. Furthermore, screw holes between the bone segments would allow intersegmental grafting during the operation if needed.

In our study, after Le Fort I osteotomy in Class III open closure patients, FEA was employed to stabilize specially designed individual fixation plates and movements in the segments using the standard 4-plate fixation method under 240 N occlusal force. In all models, the most significant part of the movement was observed in the anterior segment of the inferior segment of the maxilla. It is mentioned in the literature that stabilizing the anterior part of the upper jaw following the inferior direction after Le Fort I osteotomy, especially in front open closure cases, is challenging. This finding aligns with previous studies indicating that the region with the most movement in our study is the anterior part of the inferior segment of the maxilla (16-18).

When examining the total amount of motion across all planes, Model 1 exhibited the maximum movement, measuring 6.22 mm, while Model 2 displayed a movement amount of 0.68 mm. The order of movement in the models studied ranged from larger to smaller: Model 1 > Model 4b > Model 4a > Model 3b > Model 3a > Model 2b > Model 2a.

The maximum von Mises stress value formed on the plates and screws was found to be 6 times higher in Model 1 than in Model 2. Specifically, among the plaques designed, Model 1 showed about 3 times more stress accumulation than Model 4b, which had the highest stress accumulation value, with a thickness of 0.4 mm and 8 screws. Stresses on both plates and screws were considerably less than those of Model 1 in single-piece platters. Examining the single plate, it was observed that the stress on the plates and screws decreased as the thickness and the number of screws increased. A linear relationship between stress on plates and screws was identified, with the stress order being Model 1 > Model 4b > Model 4a > Model 3b > Model 3a > Model 2b > Model 2a. Comparatively, Huang et al. compared the standard 4-plate system with the plate produced specially for the work, reporting Von Mises stress values that were 67% less when using specially produced one-piece plates compared to the 4-plate system and 65% less when using the midevacuated optimum plates. In our study, Von Mises stress values showed a reduction of 83% on the plate compared to Model 2a, which represented the 4-plate standard system, and exhibited the most stable results among the singlepiece plates produced specially for individuals (34).

When assessing stresses in the bone, the least stress accumulation was observed in Model 4a. The difference between Model 4a, Model 3a, and Model 2a at different thicknesses using 11 screws was negligible. Stress on 8-threaded plates was more pronounced and formed in Model 3b, which had a minimum stress of 0.6 mm on 8-threaded plates. Subsequently, Model 4b on 0.4 mm paper was followed by Model 2b on 0.8 mm thickness. A plate with a thickness of 0.6 mm was found to be more effective in terms of balanced distribution of stress on balanced bone. Moreover, the results indicated that screw numbers must be kept high during fixation to ensure a balanced distribution of stress to the bone. The models were designed to ensure perfect bone/plaque compatibility. Therefore, the use of thinner plaques was considered more crucial for balanced distribution of stress on bone, considering the discrepancies that may occur on the plates matched to bone contours during surgery.

The results obtained in our study showed that the plate designed for stabilization provided more stability than fixation with 4 plates at all thicknesses. When examining stresses on screws and plates, the stress on the plates we designed was considerably less than the standard method. When considering these parameters in addition to the measurement of stress on the bone, an ideal Le Fort I osteotomy fixation would be achieved with a single piece and a thin (0.4 mm) plate fitted with as many screws (11 screws) as possible.

CONCLUSION

Achieving the best aesthetic and functional result after orthognathic surgery requires preoperative planning, transferring the planned plan to the patient, ensuring patient comfort after the operation, and preserving the obtained result in the long term. The use of patient specific designed plates for the operation with the thinnest and most durable plates for the operation plan is expected to result in high bone/plaque compatibility and ease of use during the operation. This comprehensive approach aims to transfer the operation plan to the patient completely. It is anticipated that optimal plate design may lead to lead to a decline in relapse rates in the long term, ultimately benefiting patients.

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Ethical approval: *In this study, no questionnaires, interviews, focus groups, observations, experiments, or similar methods were employed, no experiments were conducted on humans or animals, and no violation of personal data protection laws occurred. It has been declared by the corresponding author that this is a study that does not require ethics committee approval.*

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