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Evaluation of inter-maxillary fixation techniques for multi-piece Le Fort I osteotomies using finite element analysis

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Abstract. – OBJECTIVE: A strong postoperative occlusal relationship is essential for the long-term stability of the jaw relations post orthognathic surgery. In multi-piece Le Fort I osteotomy, obtaining a satisfactory inter-maxillary fixation (IMF) of the mobilized segments in the correct position and according to the preoperative plan is difficult. Herein, we aimed to evaluate three different IMF techniques (tooth-supported, bone-supported, or hybrid IMF) using finite element analysis (FEA) of the occlusal surfaces of four models: three multi-piece (lateral incisor-canine, central incisor-central incisor, and canine-first premolar) and a single one-piece Le Fort I osteotomy scenario.

MATERIALS AND METHODS: Three different IMF techniques were applied separately to three different multi-piece models and a single one-piece Le Fort I model designed using related software. Simulation brought the lower and upper jaw models to the planned occlusion. Each model's occlusal force was applied to determine their distributions under 100 N, 300 N, and 800 N loads. Forces on the maxilla and mandible during fixation, the effect of these forces on the force distribution in the occlusion, and the accumulated stresses in these regions were determined with Algor Fempro and Rhinoceros software to determine the ideal fixation method. Data obtained were interpreted and evaluated according to the advantages and disadvantages of the actual surgical scenario.

RESULTS: In all four models studied, the hybrid IMF technique was found to be the ideal IMF technique, followed by the teeth- and bone-supported IMF techniques.

CONCLUSIONS: FEA allows the manipulation of single parameters, which clinical methods cannot obtain, thereby allowing each to be examined separately. Further clinical trials are required to validate these findings.

Key Words:
Finite element analysis, Inter-maxillary fixation, Multi-piece Le Fort I, Orthognathic surgery.

Introduction

Multi-piece Le Fort I osteotomy is usually preferred for correcting a wide range of midface deformities, such as transverse deficiency/excess, asymmetry, correction of transverse and vertical deformities, and occlusal curves. A significant problem during the surgical procedure is the difficulty in performing inter-maxillary fixation, i.e., fixing the moving segments in an appropriate position following the preoperative planning[1,2]. In 2017, Meewis et al[3] discovered that the occlusion obtained in the postoperative period differed from the preoperatively planned occlusion, which was determined based on the conventional method of intraoperative inter-maxillary fixation (IMF) of multi-piece Le Fort I osteotomy[3].

Conventional surgical splints are used to transfer the preoperatively planned interdigitation of the teeth to the surgical site. Upper and lower jaw models are needed in the conventional method for splint fabrication; additionally, facial arch records and maxilla and mandible models mounted on an articulator are needed to determine the position of the upper jaw in space[4]. However, some studies[5,6] report differences in the occlusion obtained between the preoperative planning and postoperative results in the case of splints prepared using the conventional method. These differences may be attributed to the type of facial arch used, errors that occur during the articulation of the facial arch recordings, and to the lower and upper jaw models[5,6].

These splints can be produced with higher accuracy using the Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) technique compared to the conventional method[7-12]. However, despite these developments that have increased the accuracy of splint production, the desired final occlusion may not be achieved because

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of the mal-positioning of segments, especially in cases where existing teeth cannot be fixed in the appropriate position in the created splint.

Long-term stability in orthognathic surgery depends on a stable fixation and ideal postoperative occlusal relationship. Fabrication of a good splint is needed to ensure an ideal and planned occlusion, and the teeth need to be seated on every surface homogeneously during surgery. When Le Fort I surgery is performed in one piece, the lower and upper jaw teeth are occluded by IMF, and if there is no error during the splint fabrication, it is easy to achieve an excellent tooth and splint fit. This occurs since the maxillary bone and teeth function as a single unit, and IMF procedures provide stress uniformly to the teeth and splint, ensuring a tight fit. Because stable occlusion can be obtained in a one-piece Le Fort I surgery, no problems are encountered due to this osteotomy's dynamics. However, in multi-piece Le Fort I osteotomy, even with an orthodontically stable occlusion, the dynamics of each of the three segments are independent, making it difficult to achieve complete occlusion with IMF methods supported by hooks placed on teeth. In multi-piece Le Fort I surgery, segmented maxillary bone fragments are forced to rotate in the vestibular direction during IMF, which is performed by obtaining support from teeth of both arches, and this may cause the palatal/lingual aspects of the maxillary and mandibular teeth to move away from each other. Another common IMF technique is bone-supported IMF. Several studies[13-16] have demonstrated that bone anchorage is more stable than tooth anchorage. For this purpose, IMF screws in appropriate areas of the maxillary and mandibular bones can ensure the correct relationship between the jaws and teeth. However, similar mechanics may occur in the tooth-supported IMF technique, and complete occlusion and contact may not occur on the lingual/palatal aspects of the teeth.

In this study, we evaluated the inter-occlusal contact rates of various IMF techniques for the Le Fort I osteotomies using finite element analysis (FEA). The temporary IMF techniques used in multi-piece Le Fort I osteotomies during surgery have yet to be compared in any studies.

Materials and Methods

Three-dimensional maxilla and mandible virtual models were created in the STL file format. The bone tissue on the mandible and maxilla models, tooth positions, patient brackets, hooks, and 0.4 mm stainless steel arch-wires to be used in fixation were planned similarly for all scenarios. For editing and homogenizing the 3D mesh structure and for creating the 3D solid model and finite element stress analysis, a computer with the following specifications was used: Intel Xeon® R CPU 3.30 GHz processor, 500 GB Hard disk, 14 GB RAM, and Windows 7 Ultimate Version Service Pack 1 operating system, 3D scanning with Activity 880 optical scanner (smart optics Sensortechnik GmbH, Bochum, Germany), Rhinoceros 4. 0 3D modeling software (McNeel, Barcelona, Spain), VRMesh Studio (VirtualGrid Inc., Bellevue City, WA, USA), and Algor Fempro analysis software (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA, USA). The bone tissue was modeled using 3D Doctor software (Able Software, Lexington, MA, USA). The models were created geometrically using VRMesh Studio software and then converted to the STL file format for analysis. The STL file format has a universal value for three-dimensional modeling programs; there is no information loss when transferring between programs because the coordinate information of the nodes is stored in this format. Rhinoceros 4.0 software was used to create models of the maxilla with elements such as arch-wires, brackets, fixation points, 0.4 mm stainless steel wire, and single- and multi-piece Le Fort I incisions in four different clinical scenarios (one piece Le Fort I, central incisor-central incisor, lateral incisor-canine, and canine-premolar), and the models were then imported into Algor Fempro software (Figures 1, 2, and 3).

This study examined three multi-piece Le Fort I and one-piece Le Fort I scenarios widely used in literature. The multi-piece Le Fort I, the maxillary model, was divided into three different setups. The osteotomy cut started between the central incisor-central incisor, between lateral incisor-canine, or between canine-premolar teeth. Next, the osteotomy cuts between the related teeth were combined with being positioned in the paramedian region, and the resulting pieces were segmented to run parallel to the maxillary midline (Figures 1, 2, and 3).

Three different IMF techniques were applied separately to three different multi-piece models, and a single one-piece Le Fort I model was designed using related software. Simulation brought the lower and upper jaw models to the planned occlusion. Finally, using the three different techniques, FEA with the Algor software was used to evaluate the occlusal surfaces. The technique that created the most interocclusal contact be-

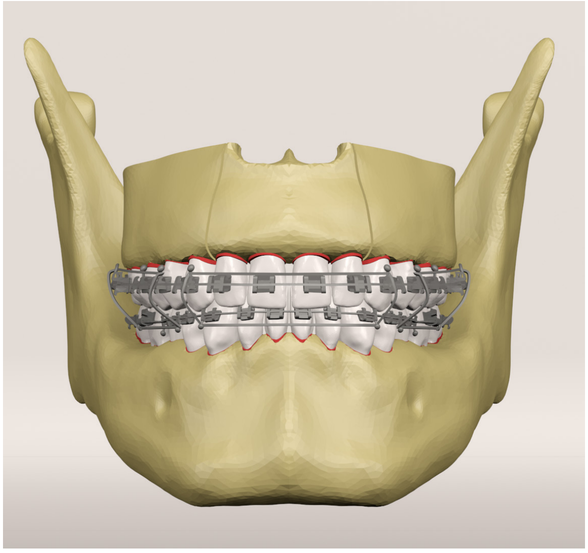

Figure 1. Multi-piece Le Fort I osteotomy design with the osteotomy cut between lateral incisor and canine tooth.

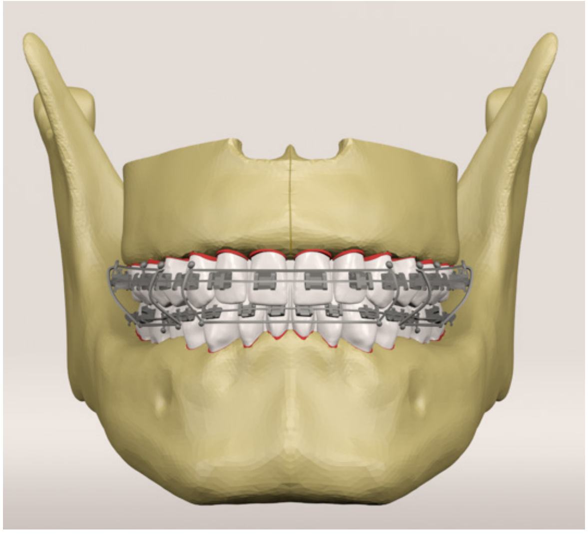

Figure 3. Multi-piece Le Fort I osteotomy design with the osteotomy cut between two central incisors.

tween the two jaws was investigated by assessing the dynamics of four different osteotomy designs (four study models) and their force distribution on the occlusal surfaces under tooth-supported, bone-supported, or hybrid IMF.

Application of the Inter-Maxillary Fixation Methods

Tooth-supported inter-maxillary fixation method

IMF was achieved using all teeth of the upper and lower jaws and hook support. Stabilization was provided by hooks placed between two teeth of opposing arches. A 0.4 mm steel wire was used to support these hooks; resultantly, the teeth in the lower and upper jaws were brought into occlusion. For this purpose, a connection material to simulate the steel wire was applied to the right side of the lower and upper jaw models, starting from the hooks on teeth 16-46 and ending at the hooks on teeth 14-44 while receiving support from the intervening hooks. Additionally, a connection material to simulate the steel wire was applied to the anterior region of the lower and upper jaw models, starting from the hooks on teeth 13-43 and ending at the hooks on teeth 23-33, while receiving support from the intervening hooks (Figure 4). This fixation method was applied to four different Le Fort I scenarios without any modifications.

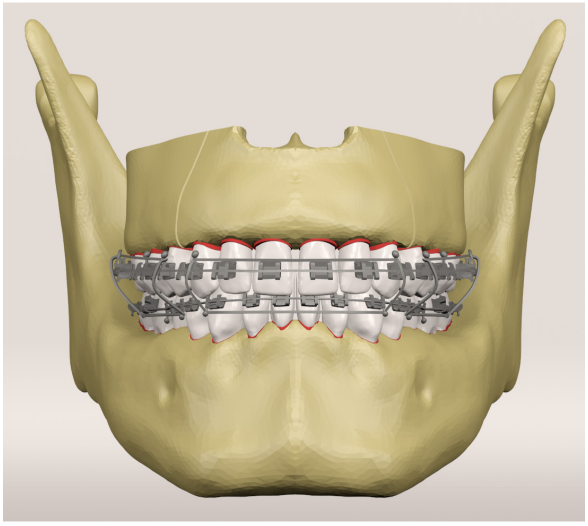

Figure 2. Multi-piece Le Fort I osteotomy design with the osteotomy cut between canine and premolar teeth.

Hybrid inter-maxillary fixation method

Four IMF screws were placed as follows: on the alveolar bone between teeth 11-21, at point B (most concave point) on the mandibular symphysis, on the alveolar bone between teeth 35-36, and the alveolar bone between teeth 45-46 using the hybrid IMF method. Arch wires connected these four fixation points in the following ways: point B was connected to the fixation point between 11-21; the fixation point between teeth 35-36 was fixed to the arch-wire of the maxillary teeth at the midpoint of tooth 26; and the fixation point between teeth 45-46 was fixed to the arch-wire of the maxillary teeth at the midpoint of tooth 16 (Figure 5-6).

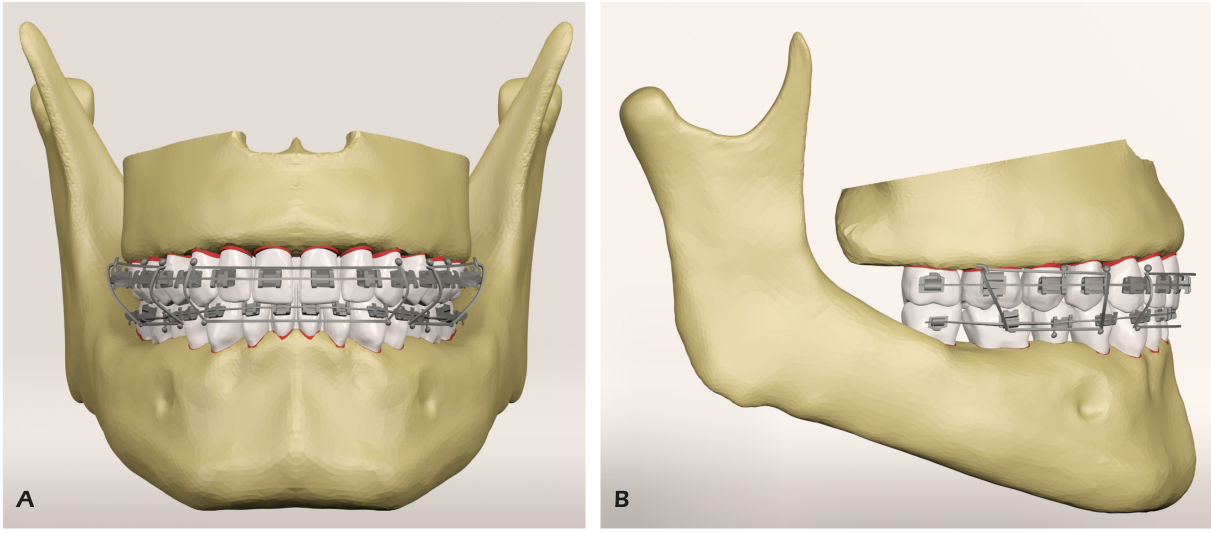

Figure 4. Tooth-supported intermaxillary fixation method, wherein the fixation points on the maxilla (**A**) and posterior region (**B**) are demonstrated with the positioning of the connections.

An osteotomy cut was placed in the maxillary midline (between teeth 11-21) in the Le Fort I osteotomy scenario, and the IMF screw positions were as follows: to provide bone support in the maxillary anterior region, IMF screws were placed between alveolar bone teeth 11-12 and on the alveolar bone between teeth 21-22; all other fixation points were used as in the other two models (Figure 7).

Bone-supported inter-maxillary fixation method

IMF was simulated by placing fixation points on the alveolar bone in the anterior region: the alveolar bone between teeth 12-13, the alveolar bone between teeth 22-23, and point B in the mandible. For the application of IMF in the posterior region, the fixation points were as follows: alveolar bone between teeth 15-16; alveolar bone between teeth 15-16, 45-46; alveolar bone between teeth 25-26; and alveolar bone between teeth 35-36. Fixation points were connected to the material used to simulate the steel wire (Figure 8).

Based on the stabilization method and the maxillary segmentation pattern used in each multi-piece and one-piece maxillary osteotomy, the occlusal surfaces of the teeth and the maximum stress areas on the splint in the possible surgical scenario were evaluated. The mutual relationships between the teeth and the contact or non-contact zones that may

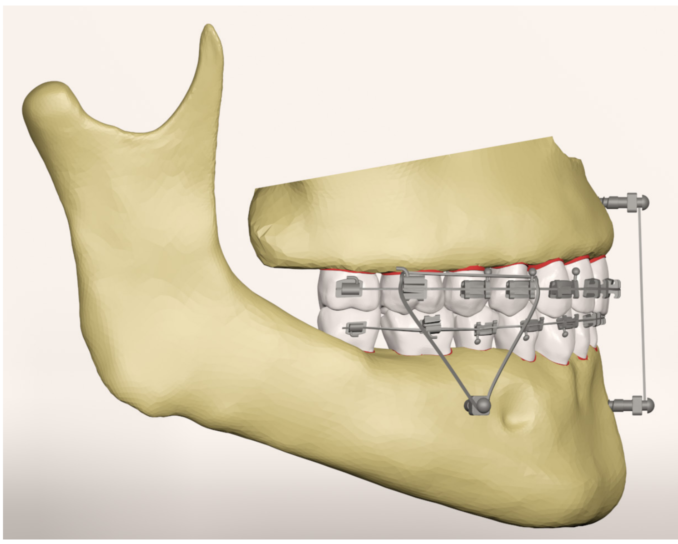

Figure 5. Hybrid intermaxillary fixation method with the posterior fixation points and the positions of the connections.

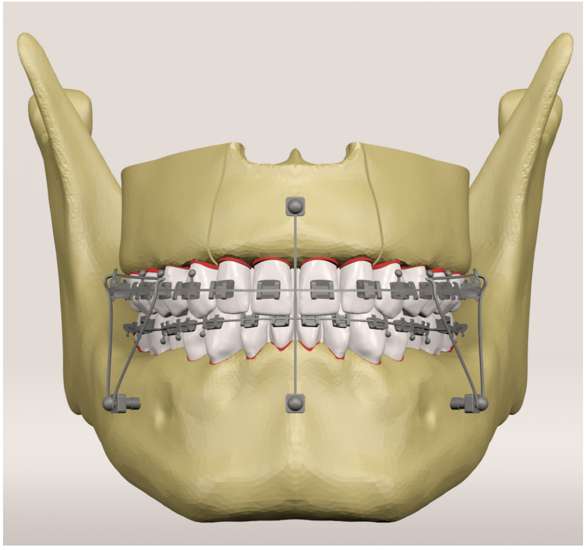

Figure 6. Hybrid intermaxillary fixation method with the fixation points and position of connections in the anterior region.

occur with the splint were determined to evaluate the stability and relapse problems in the postoperative period. We attempted to determine the most reliable and accurate method for stabilizing multi-piece Le Fort I fractures for the surgeon and patient in the postoperative period.

Material Properties

The models produced in the VR Mesh software were transferred to the Algor software as surface data in the STL file format. The models must have fully meshed for the Algor software to perform the analysis.

The models were formed from as many elements as possible in the meshing process with ten node points (brick type). When necessary, elements with fewer nodal points were used to complete the structure in the regions near the center of the models. This modeling technique created the highest-quality network structure with the most node-point elements to facilitate the calculation. The upright and narrow regions found in the jaw models, which make the analysis process difficult, were cleared of linear elements and regularized.

The models were transformed into solid models in the form of Bricks and Tetrahedral elements. In the Bricks and Tetrahedra solid modeling system, 8-node elements were used as much as possible by the Fempro model. In cases where 8-node elements could not reach the required details, 7-node, 6-node, 5-node, and 4-node elements were used.

All the models were considered linear, homogeneous, and isotropic materials. The homogeneity of a material indicates that its mechanical properties are similar for each structural element. In contrast, isotropy refers to a situation in which the material properties of the structural element are the same in all directions. Linear elasticity is the proportional variation of the deformation or strain of a structure under applied forces. For the study to produce realistic results, as many elements as possible (as much as the program allowed) were selected by considering the dimensions of the jawbone model selected by us.

The 0.4 mm wire and brackets were scanned using a Smart Optics three-dimensional scanner (Sensortechnik GmbH, Bochum, Germany) three-dimensionally. The models obtained in the STL file format were then exported to the Rhinoceros software version 4.0. The Boolean method in the Rhinoceros software (McNeel, Barcelona, Spain) was used to align the brackets, fixation points, 0.4 mm wire, and bone tissues, and force transfer was performed.

For modeling the bone tissues, computerized tomography was first performed for the patient using a 3M Iluma CBCT device (Imtec Corporation, Oberursel, Germany) with the following parameters: 40-second x-ray mode at 120 KvP and a tube current of 3.8 mA. The X-rays were transferred to the 3D-doctor software, where the bone tissue was decomposed after considering the

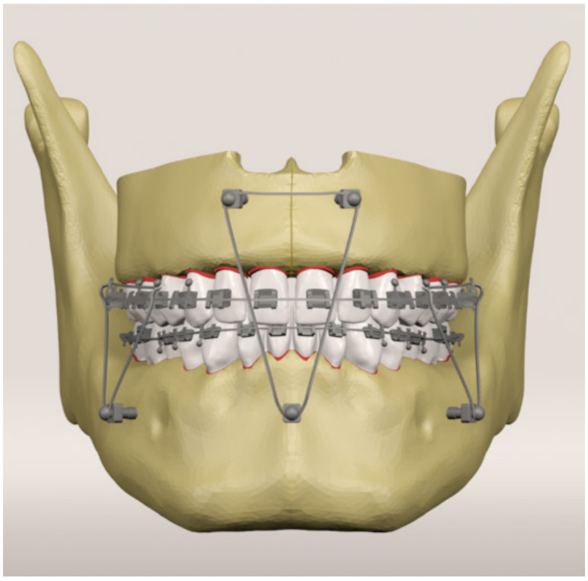

Figure 7. Positioning of anterior fixation points and connections in the multi-piece Le Fort I osteotomy model, where the osteotomy line is between teeth 11-21.

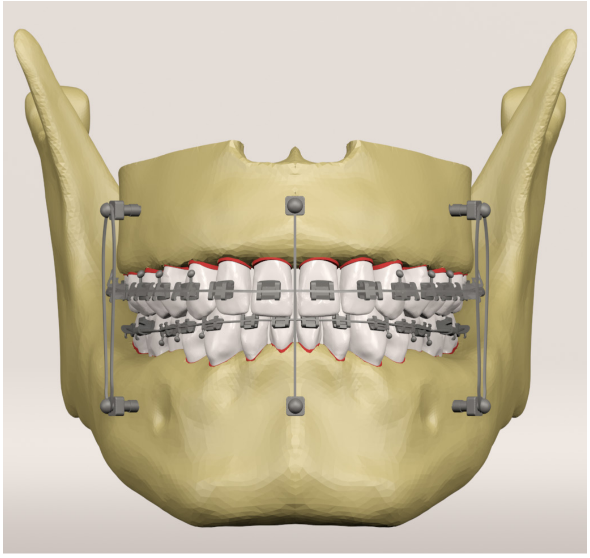

Figure 8. Positioning of anterior and posterior fixation points and connections in bone-supported intermaxillary fixation method.

Hounsfield values using the "Interactive Segmentation" method. After the segmentation process, a three-dimensional model was obtained by the "3D Complex Rendering" method, and bone tissue was modeled in this way. Spongiose bone was obtained from bone tissue using the offset method, and force transfer was provided by making the necessary adjustments. In this way, the maxilla and mandible cortical bone, spongy bone, 0.4 mm wire, brackets, and fixation points were moved to the model to reflect its actual morphology. The simulations were placed in the correct coordinates in three-dimensional space using the Rhinoceros software, and the modeling process was completed. The modeling performed in Rhino was transferred to Fempro software by preserving the three-dimensional coordinates.

Previously published data was used to determine the muscle weight factors, scaling factors, unit vector coordinates, and knot numbers to model the load sets for a unilateral molar clenching task[17].

Limitation Conditions

The model was fixed at the lower and posterior parts of the jawbone such that it had zero movements in each degree of freedom (DOF). The static linear analysis with a three-dimensional finite element stress analysis method was used for evaluation.

After creating the geometric model using VRMesh software, STL files were transferred to Algor Fempro software. Aligning the maxilla and mandible models with the Algor Fempro software and identifying the components of the maxilla and mandible and the material of the tooth structures is necessary. The material values describing each model (modulus of elasticity and Poisson's ratio) were provided for this purpose. In this software, the properties of the solid body were set as linear elasticity, homogeneity, and isotropy.

Accordingly, preliminary work was done on three-dimensional CBCT images of a Class 2 patient. Geometric models, meshwork, virtual maxillary and mandibular models were created. Fixation points were created on the maxillary and mandibular models in a virtual environment where Le Fort I osteotomy incisions were made. Three different fixation techniques were applied to four different clinical scenarios. The results were then evaluated and interpreted. Any statistical comparison was not applied.

Virtual Lateral-Canine Multi-Piece Le Fort I Model

On a three-dimensional maxillary model obtained from the patient's CBCT scan and designed in a virtual environment, the osteotomy cuts between the lateral and canine teeth were segmented to position them in the paramedian region and parallel to the maxillary midline (Figure 1).

Virtual Canine-Premolar Multi-Piece Le Fort I Model

On a three-dimensional maxilla model obtained from the patient's CBCT scan and designed in a virtual environment, the osteotomy cuts between the canine and premolar teeth were positioned in the paramedian region and segmented so that they converge and run parallel to the maxillary midline (Figure 2).

Virtual Central-Central Multi-Piece Le Fort I Model

On the three-dimensional maxilla model obtained from the patient's CBCT scan and designed in the virtual environment, in addition to the conventional Le Fort I osteotomy, the osteotomy cuts between the central incisor and central incisor were positioned in the paramedian region. The pieces were segmented to parallel the maxillary midline (Figure 3).

One-piece Le Fort I Model

One-piece Le Fort I osteotomy was performed on a three-dimensional maxillary model designed in a virtual environment, obtained from the patient's CBCT scan.

Table I. Determination of force distribution on the occlusal surface of each tooth of the lower jaw using finite element analysis.

Tooth numered as per the fdi system	Multipiece Le Fort I, interdental osteotomies between lateral incisors and canines	Multipiece Le Fort I, interdental osteotomies between canines and premolars	Multipiece Le Fort I, interdental osteotomies between central incisor and central incisor	One-piece Le Fort I osteotomy
41	I>II>III	I>II>III	II>I>III	II>I>III
42	I>II>III	I>II>III	II>III>I	II>I>III
43	I>II>III	I>II>III	I>II=III	I>II=III
44	II>I>III	I>II>III	II>III>I	I>II=III
45	II>I>III	II>I>III	II>III>I	II>III>I
46	II>I>III	II>I>III	II>III>I	II>I>III
47	II>I>III	II>I=III	II>III=I	II>I>III
31	I>II>III	I>II>III	II>I>III	II>I>III
32	I>II>III	I>II>III	II>III>I	II>III=I
33	I>II>III	I>II>III	I>II=III	I>II=III
34	II>I>III	I>III>II	II>III>I	II>I>III
35	II>I>III	II>I>III	II>I>III	II>III>I
36	II>I>III	II>III>I	II>III>I	II>I>III
37	II>I>III	II>III>I	II>III=I	II>I>III

(I: Tooth-supported Intermaxillary Fixation Technique, II: Hybrid Intermaxillary Fixation Technique, III: Bone-supported Intermaxillary Fixation Technique).

With FEA, force vectors were applied to these fixation points and connections in various directions. Forces on the maxilla and mandible during fixation, the effect of these forces on the force distribution in the occlusion, and the accumulated stresses in these regions were tried to be determined with Algor Fempro and Rhinoceros software to determine the ideal fixation method. Each model's occlusal force was applied to determine their distributions under 100 N, 300 N, and 800 N loads. The data obtained were interpreted and evaluated according to the advantages and disadvantages of the actual surgical scenario.

The occlusal surfaces of the teeth and maximum stress areas on the splint were evaluated following the literature, based on the stabilization method and maxillary segmentation pattern, after related maxillary osteotomies[18,19]. Based on these scenarios, we aimed to determine postoperative stability and relapse problems by determining the contact or non-contact zones that may occur in the mutual relationship between the teeth and splint.

Results

Determination of force distribution on the occlusal surface of each tooth of the lower jaw, upper jaw, and in the regions of the upper and lower jaws using finite element analysis are displayed in Tables I, II, and III, respectively, and Figures 9-12.

The hybrid IMF technique was determined to be the best among all one-piece and multi-piece Le Fort I models (central incisor-central incisor, lateral incisor-canine, canine-premolar) in terms of inter-occlusal contact. The conventional IMF technique was the second-best in the one-piece Le Fort I and lateral incisor-canine, inter-canine-premolar multi-piece Le Fort I models, followed by bone-supported IMF.

However, the bone-supported intermaxillary fixation technique ranked second in the central incisor-central incisor multi-piece Le Fort I model. The conventional inter-maxillary technique was a minor ideal of the techniques applied.

Central incisor - central incisor Multi-piece Results of the Le Fort I model's finite element analysis for the inter-occlusal contacts of the upper and lower jaws for the Dental-assisted Intermaxillary Fixation technique (1), the Hybrid Intermaxillary Fixation method (2), and the Bone-assisted Intermaxillary Fixation method with bone support (3) are shown. According to Stress von Mises, the red areas of the occlusal surfaces in the figures are those where stress accumulation is most significant, followed by the orange, yellow, green,

Table II. Determination of force distribution on the occlusal surface of each tooth of the upper jaw using finite element analysis.

Tooth numered as per the fdi system	Multipiece Le Fort I, interdental osteotomies between lateral incicors and canines	Multipiece Le Fort I, interdental osteotomies between canines and premolars	Multipiece Le Fort I, interdental osteotomies between central incisor and central incisor	One-piece Le Fort I osteotomy
11	II>I>III	I>II>III	II>III>I	I>III>II
12	I>II>III	I=II=III	III>I>II	I=III>II
13	II>I>III	I>II>III	II>III>I	I>III=II
14	II>I>III	II>I>III	II>III>I	II>I>III
15	II>I>III	II>I>III	III>II>I	III>II>I
16	II>I>III	II>I>III	I>III>II	II>I=III
17	II>I>III	II>I>III	II>I>III	II>I>III
21	II>I>III	II>I>III	II>III>I	I>III>II
22	I>II>III	I>II>III	II=III>I	I=III>II
23	II>I>III	I>II=III	II>I>III	I>III>II
24	II>I>III	II>I>III	II>III>I	II>I>III
25	II>I>III	II>I>III	I>III>II	III>I>II
26	II>I>III	II>I>III	I>II>III	I=III>II
27	II>I>III	II>I>III	II>I>III	II>III>I

(I: Tooth-supported Intermaxillary Fixation Technique, II: Hybrid Intermaxillary Fixation Technique, III: Bone-supported Intermaxillary Fixation Technique).

Table III. Determination of force distribution in specific regions of the upper and lower jaws using finite element analysis.

Upper jaw	Multipiece Le Fort I, interdental osteotomies between lateral incisors and canines	Multipiece Le Fort I, interdental osteotomies between canines and premolars	Multipiece Le Fort I, interdental osteotomies between central incisor and central incisor	One-piece Le Fort I osteotomy
Incisor region	II>I>III	I>II>III	II>III>I	I>III>II
Premolar region	II>I>III	II>I>III	II>III>I	II>III>I
Molar region	II>I>III	II>I>II	I>II>III	II>I>III
Lower jaw	**Multipiece Le Fort I, interdental osteotomies between lateral incisors and canines**	**Multipiece Le Fort I, interdental osteotomies between canines and premolars**	**Multipiece Le Fort I, interdental osteotomies between central incisor and central incisor**	**One-piece Le Fort I osteotomy**
Incisor region	I>II>III	I>II>III	II>I>III	II>I>III
Premolar region	II>I>III	II=I>III	II>III>I	II>III>I
Molar region	II>I>III	II>III>I	II>III>I	II>I>III

(I: Tooth-supported Intermaxillary Fixation Technique, II: Hybrid Intermaxillary Fixation Technique, III: Bone-supported Intermaxillary Fixation Technique).

and blue areas, in that order. A better occlusion is obtained as the stress distribution on the occlusal surfaces increases (Figure 9).

Lateral incisor - canine Multi-piece Results of the Le Fort I model's finite element analysis for the inter-occlusal contacts of the upper

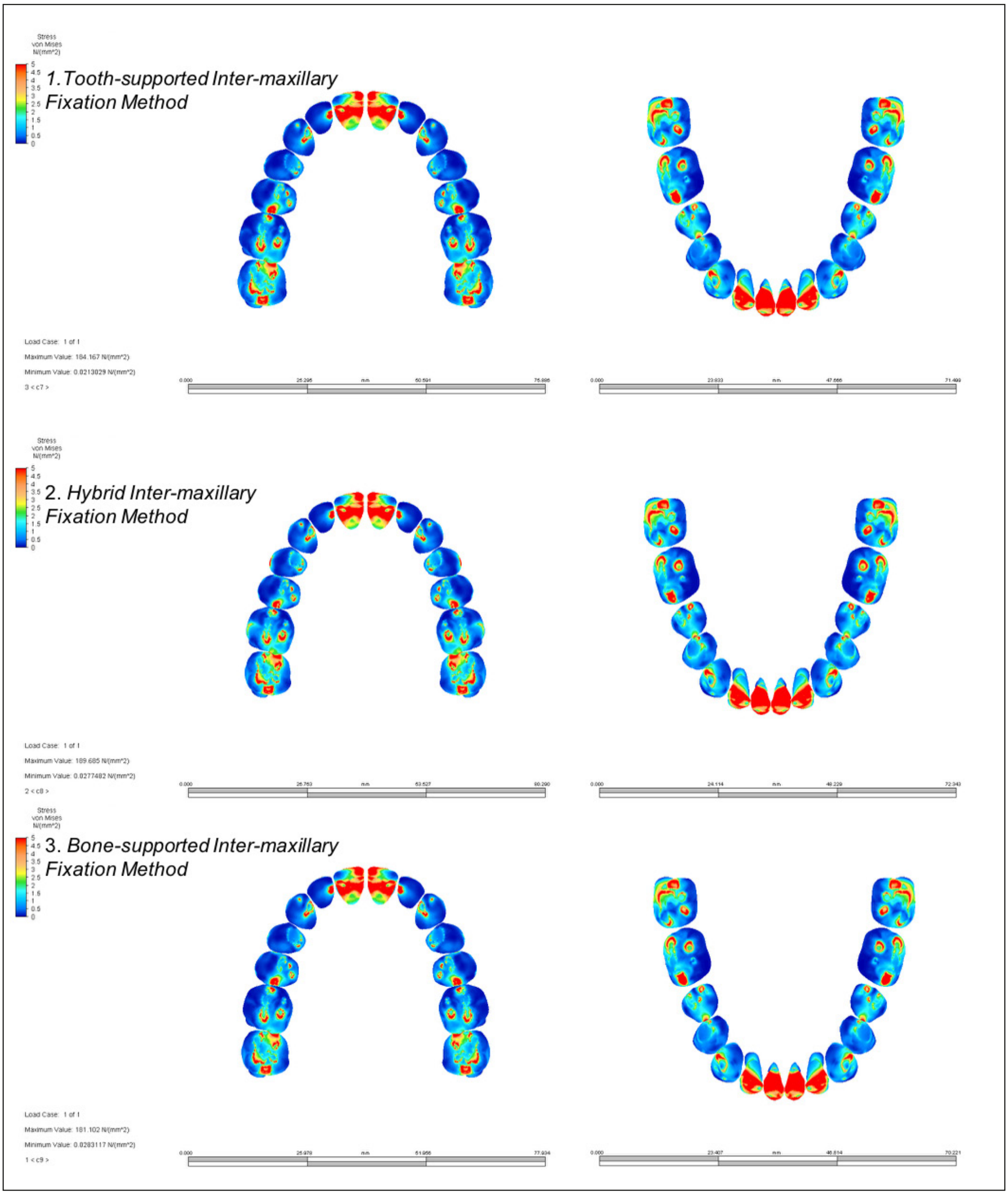

Figure 9. Central incisor-central incisor multi-piece Le Fort I Model with finite element analysis results for upper and lower jaw's inter-occlusal contact.

and lower jaws for the Dental-assisted Intermaxillary Fixation technique (1), the Hybrid Intermaxillary Fixation method (2), and the Bone-assisted Intermaxillary Fixation method with bone support (3) are shown. According to Stress von Mises, the red areas of the occlusal surfaces in the figures are those where stress accumulation is most extraordinary, followed by the orange, yellow, green, and blue areas, in that order. A better occlusion is obtained as the stress distribution on the occlusal surfaces increases (Figure 10).

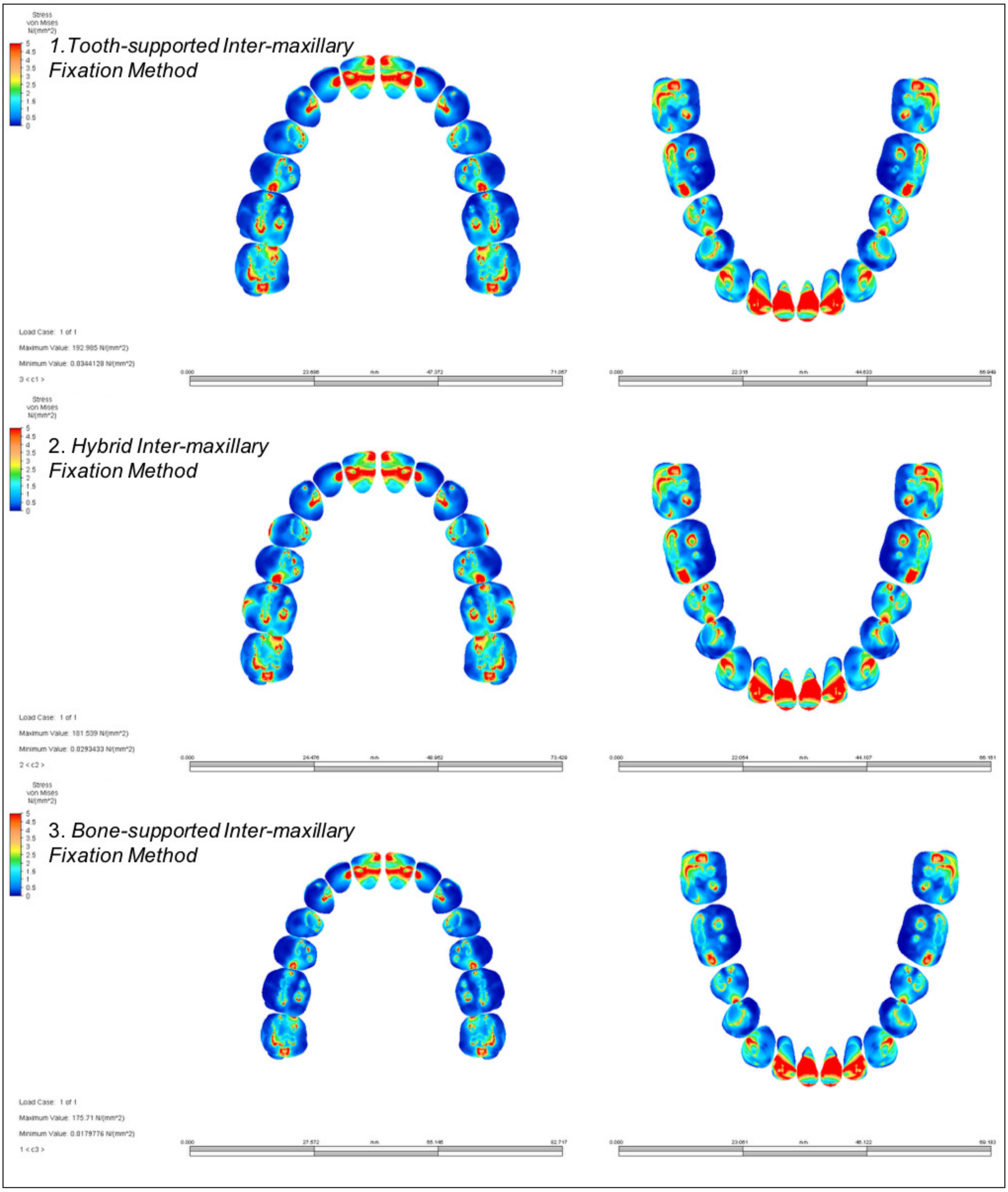

Figure 10. Lateral incisor-canine multi-piece Le Fort I Model with finite element analysis results for upper and lower jaw's inter-occlusal contact.

Canine - premolar Multi-piece Results of the Le Fort I model's finite element analysis for the inter-occlusal contacts of the upper and lower jaws for the Dental-assisted Intermaxillary Fixation technique (1), the Hybrid Intermaxillary Fixation method (2), and the Bone-assisted Intermaxillary Fixation method with bone support (3) are shown. According to Stress von Mises, the red areas of the occlusal surfaces in the figures are those where stress accumulation is most remarkable, followed by the orange, yellow, green, and blue areas, in that order. A better occlusion is obtained as the stress distribution on the occlusal surfaces increases (Figure 11).

Results of the One - piece Le Fort I model's finite element analysis for the inter-occlusal contacts of the upper and lower jaws for the Dental-assisted Intermaxillary Fixation technique (1), the Hybrid Intermaxillary Fixation method (2), and the Bone-assisted Intermaxillary Fixation method with bone support (3) are shown. According to Stress von Mises, the red areas of the occlusal surfaces in the figures are those where stress accumulation is most remarkable, followed by the orange, yellow, green,

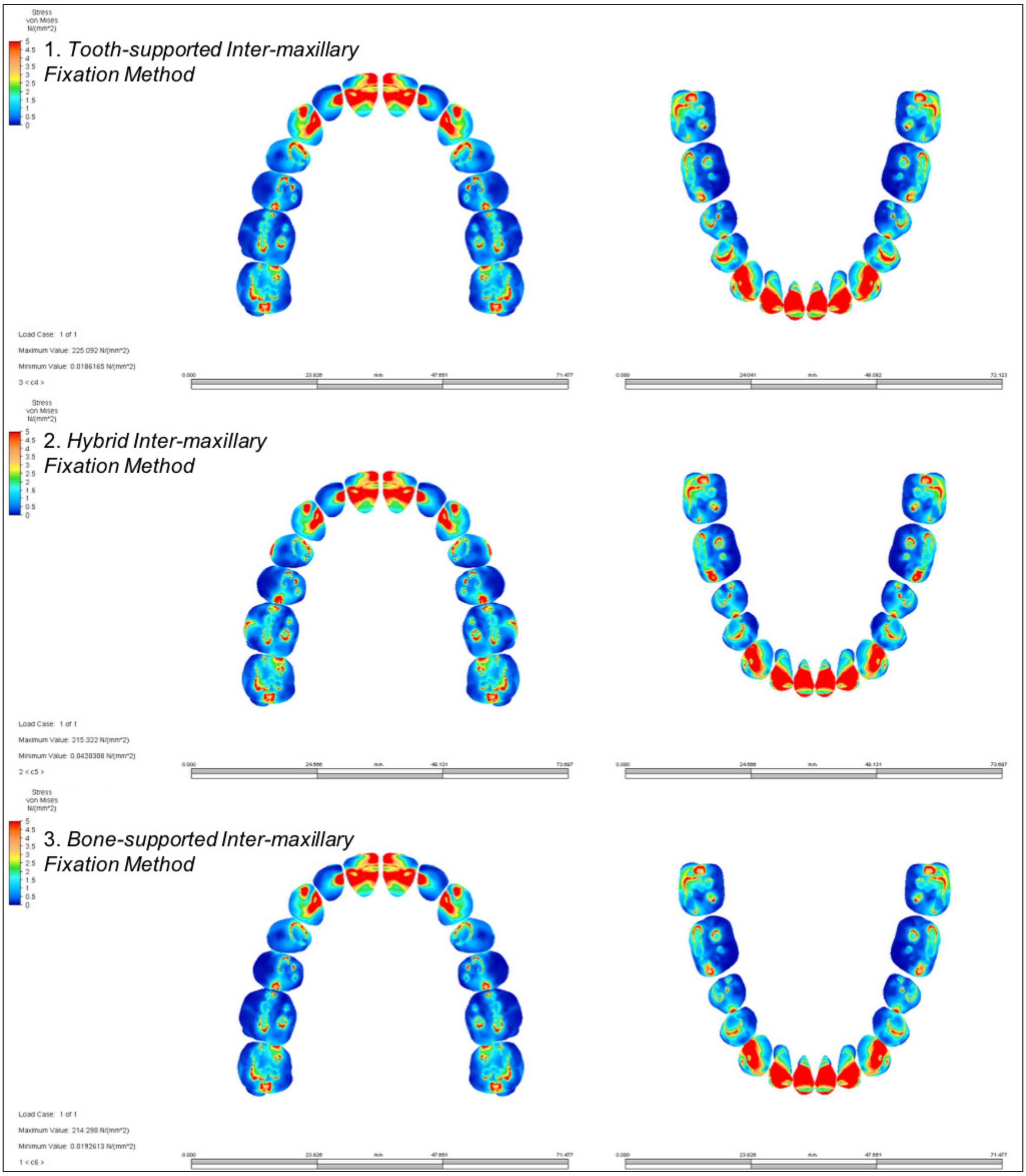

Figure 11. Canine-Premolar multi-piece Le Fort I Model with finite element analysis results for upper and lower jaw's inter-occlusal contact.

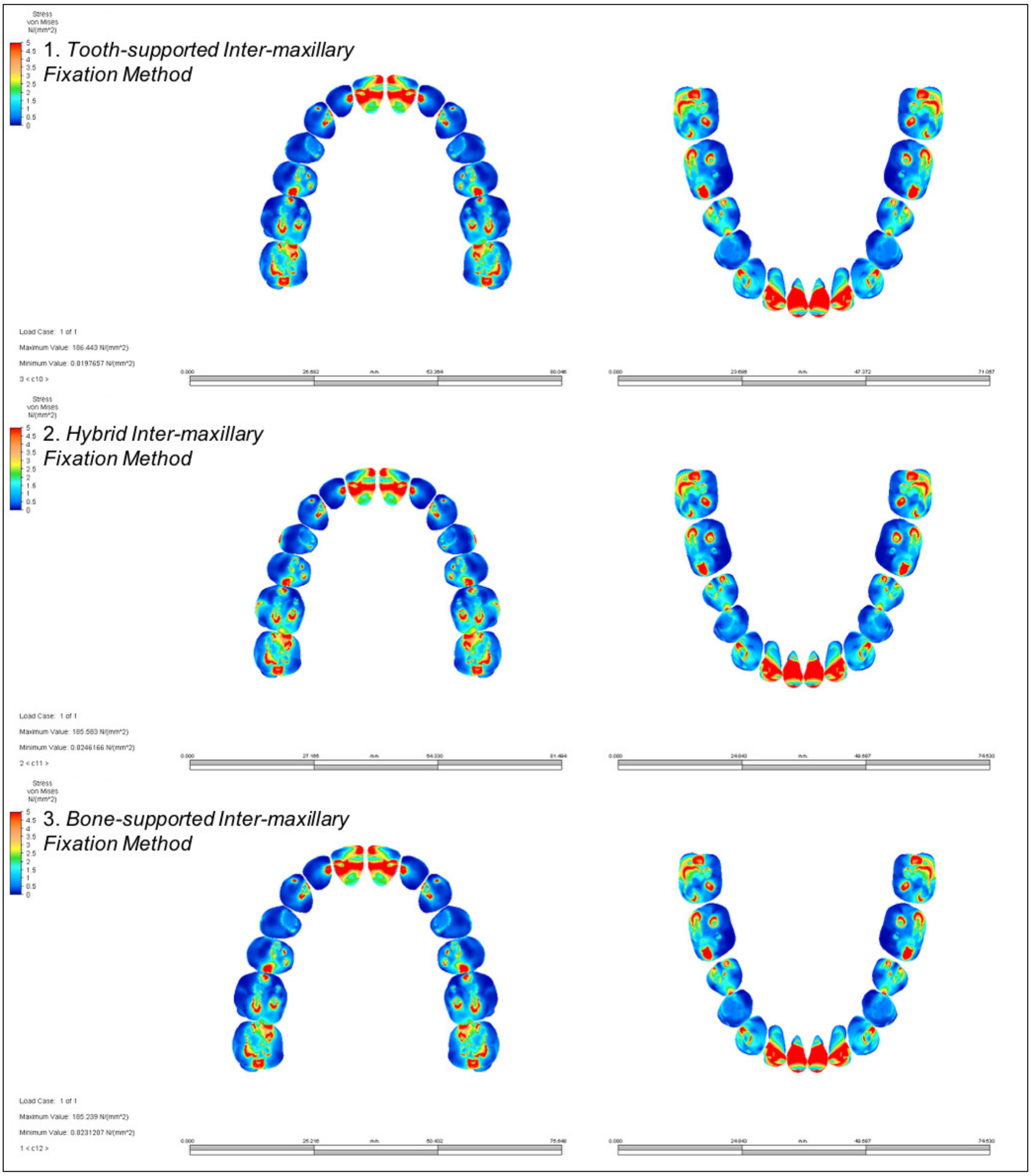

Figure 12. One-piece Le Fort I Model with finite element analysis results for upper and lower jaw's inter-occlusal contact.

and blue areas, in that order. A better occlusion is obtained as the stress distribution on the occlusal surfaces increases (Figure 12).

Discussion

We evaluated the dynamics of four different osteotomy designs on occlusal surfaces under tooth-supported, bone-supported, or hybrid fixation methods and attempted to determine the ideal design. Force distribution was determined using FEA at the occlusal surface level.

Transverse maxillomandibular deficiency is a common complication associated with dentofacial deformities. According to Proffit et al[20], 30% of the patients who seek consultation for dentofacial deformities complain of transverse maxillary deficiency. Together with vertical and sagittal motion, multi-piece surgery permits independent transverse maxillary movements for each surgical segment. Furthermore, the multi-piece Le Fort I allows for one-stage surgical correction of the dual-plane maxilla, i.e., correction of diastemas, transverse malocclusions, and open bites. However, maxillary expansion is considered the least stable surgical procedure for multi-piece treatment[21]. Stability problems may be attributed to many factors, including masticatory muscle activity, incorrect orthodontics, and intraoperative complications. Additionally, postsurgical instability may be attributed to insufficient maxillary mobilization, surgical movement, insufficient bone grafting soft tissue tension, and segmental stabilization[21-24].

Stabilization problems and future relapses occur mainly due to the inability to achieve an ideal occlusion with IMF during operation[21,23-28] fully. Therefore, an ideal IMF technique is required during surgery. Various studies[29,30] have compared inter-maxillary fixation screws, Erich arch bars, embrasure techniques, Eyelet interdental wiring, and combined arch bars with an inter-maxillary fixation screw.

In our study, the hybrid IMF technique was the ideal model among all the one-piece and multi-piece Le Fort I models. Bone and teeth anchoring can be used simultaneously for better IMF during surgery. The hybrid IMF technique combines the Erich arch bar technique and IMF screws; additionally, it is a commonly reported method for trauma. Studies[29,30] have shown that the hybrid IMF technique is effective. In a retrospective study[29] of 50 patients who undergone surgery for mandibular fractures, Chao et al[29] compared two methods of IMF in terms of complications rate (Group I, n=25: Erich bar and secured with circumdental wires; Group II, n=25: titanium arch bars fixed with maxillary and mandibular screws). The bone-supported arch bar fixation technique may be an alternative to the Erich arch bars secured with circumdental wires. When these two techniques were compared, malocclusion was observed in two patients in Group I, while there was no malocclusion in Group II. We believe that this is because IMF with a bone-supported arch bar can benefit from the advantages of both the arch bar (similar to the teeth-supported IMF technique in our study) and IMF techniques performed with an IMF screw (similar to the bone-supported inter-maxillary technique in our study).

Rothe et al[30] compared three different inter-maxillary fixation techniques: Erich arch bar, IMF screw, and a modified technique (Erich arch bar + IMF screw) in terms of postoperative stability after achieving the inter-maxillary fixation, mucosal growth, and complication encountered for inter-maxillary fixation. They reported[30] that the best IMF technique for postoperative stability was the Erich arch bar, followed by the modified technique (Erich arch + IMF screw), and then the IMF screw technique alone. Because the modified arch bar was significantly more stable than the IMF screws, they suggested that modified arch bars may be a suitable option for patients requiring long-term IMF[30].

We reviewed studies[31,32] that compared the embrasure wire technique to the hybrid technique, considering them similar. Tracy and Gutta[31] reported that the incidence of postoperative malocclusion was slightly higher in the arch bar group (7.5%) than in the embrasure wire group (6%). According to Satpute et al[32], the embrasure wire technique was much faster than the Erich bar technique for mandibular fractures, but the provision of stable occlusion was worse.

In our study, the tooth-supported IMF technique is the second-best in the one-piece Le Fort I, lateral incisor-canine, and canine-premolar multi-piece Le Fort I models, followed by the bone-supported IMF technique. It has shown that the arch bar technique is superior to the teeth-supported IMF technique. In their study, Nandini et al[33] randomly divided 20 mandibular fracture patients into two equal groups and compared the two inter-maxillary fixation techniques according to their advantages and disadvantages by using “Dentaurum” Erich Arch bar (group I) in one group and inter-maxillary fixation screws (group II) in the other group. Stability comparisons at the first and sixth postoperative weeks revealed that it was 80% adequate and 20% inadequate in group I and 70% adequate and 30% inadequate in group II[33]. While some studies[33] have shown that the IMF technique with the arch bar is more advantageous, others[34] have shown that the IMF technique with screws is more advantageous.

According to a randomized clinical study by Van der Berg et al[34], which compared the IMF technique performed with an anchor screw *vs.* that performed with an arch bar, it was observed that the anchor screw IMF developed fewer complications (needle stinging wound, malocclusion, pain scores) compared to the arch bar technique.

We believe that this is because titanium screws significantly improve bone anchorage. Studies[35-37] have reported that titanium screws are often used to increase anchorage.

Studies[38-40] have shown that the IMF screw technique is an alternative technique that shortens the operation time and reduces gingival health and complications, such as pinprick injuries. Furthermore, some researchers[38,41-44] believe that the IMF screw is a reliable alternative to the arch bar for trauma and orthognathic patients.

According to Choi et al[45], for 66 patients with mandibular jaw fractures, the procedure time was found to be shorter. The malocclusion rate (that required orthodontic treatment) was lower in the IMF screw technique than that in the traditional arch bar technique (n=21) and modified techniques with IMF screws (n=35) (14.3% malocclusion rate in the IMF screw system and 19.1% in the traditional arch bar system)[45].

Ingole et al[46] conducted a study on 50 patients with displaced mandibular fractures (25 with IMF screws, 25 with eyelet interdental wiring); they stated that IMF screws could be an alternative to other IMF techniques with its satisfactory occlusion, cost-effectiveness, and easy applicability to provide IMF in closed reduction treatments and intraoperative open reduction treatments of mandibular fractures[46].

Ueki et al[47] compared two groups of patients with mandibular setback surgery treated with or without an IMF screw. They concluded that there was no significant difference in skeletal change between the two groups with and without IMF screws for most measures. However, they observed that the IMF screw, which acted as a rigid anchor for IMF, was helpful in orthognathic surgery[47].

In contrast to the other models in our study, the bone-supported IMF technique performed second in the central incisor-central incisor multi-piece Fort I model, while the teeth-supported IMF technique was the least ideal. We believe this was because the teeth-supported IMF performed during the surgery had similar disadvantages as the arch bars used in trauma. We believe that the central incisor-central incisor paramedian osteotomy cut allows the movement of the teeth in the lateral and extrusion directions, fails to provide an excellent occlusal fit, and has skeletally less stable and weaker anchorage compared to the IMF screw method. The results of Baurmash et al[48] also support this thesis, which states that the disadvantages of an arch bar include movement of the teeth in the lateral and extrusion directions and that the constant traction applied to the wire may disperse the broken parts and possibly cause additional complications[48].

To the best of our knowledge, there is no published report on this topic in the literature, and we performed this study to find an ideal IMF method during the multi-piece Le Fort I operation. The FEA method is widely used to investigate stresses in the medical field, where clinical simulations could be more practical and challenging to undertake[49]. Studies[50,51] have reported the accuracy of FEA in describing the biomechanical behavior of bone samples.

In cases with many complex variables that need to be evaluated, FEA allows the manipulation of single parameters, which cannot be obtained by clinical methods, thereby allowing each to be examined separately. This study can be repeated as often as desired, and patients are not exposed to potential risks. This allows new materials and techniques to be tested quickly.

Limitations

The most severe limitations of the FEA are its oversimplifications and assumptions. In addition, in anatomical bone modeling, reflecting the anatomy morphology, etc., the FEA must fully provide geometric precision, and the analyses differ according to the material constants used[52,53].

Conclusions

Based on our results, we propose that using the hybrid IMF method during surgery in the three different Le Fort I surgical models and the one-piece Le Fort I surgery model widely used in the literature can reduce relapse and stabilization problems. However, the clinical condition may need to be more precisely represented in this software-driven *in vitro* investigation. So, clinical evaluation should be added to future FEA research about multi-piece Le Fort I stability for each IMF method. So long- and short-term stability of these methods will be evaluated in the clinical setting. Although the results of FEA can be used to identify new techniques without risk, more studies on this subject are needed because of its limitations.

Conflict of Interest
The Authors declare that they have no conflict of interests.

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Authors' Contributions
All authors contributed to the study's conception and design. All authors wrote the first draft of the manuscript, and they commented on all versions of the manuscript. All authors read and approved the final manuscript.

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Availability of Data and Materials
The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics Approval
The article did not include clinical patients and only included software-based results; none of the authors have conducted any investigations using human or animal subjects. Therefore, it did not require ethical approval.

Informed Consent
Not applicable.

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