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Comparative evaluation of different fixation techniques for sagittal split ramus osteotomy in 10 mm advancements. Part two: Finite element analysis

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A R T I C L E I N F O

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Purpose: To evaluate three rigid, stable fixation methods for sagittal split ramus osteotomy (SSRO), using finite element analysis. The hypothesis is that a customized miniplate presents better stress concentration and distribution.

Materials and methods: A 3D model of a hemimandible was created, and a 10-mm-advancement SSRO was simulated and fixed as follows: 3-DCP group — one custom miniplate fixed by eight screws; 4-H2P group — two miniplates of four holes each, fixed by eight screws; and 6-H2P group — two miniplates of six holes each fixed by 12 screws. After a vertical loading of 100 N, the values for von Mises stress, modified von Mises stress, and maximum and minimum principal stresses were measured.

Results: The area of maximum principal stress was similar for the three groups — located in the upper miniplate, in the screw near the proximal segment osteotomy. The maximum von Mises stresses were 1580.4 MPa, 1005 MPa, and 977.56 MPa for the 3DCP, 4-H2P, and 6-H2P groups, respectively, showing an allowable displacement of 2.57 mm, 1.62 mm, and 1.52 mm for the 3DCP, 4-H2P, and 6-H2P groups, respectively.

Conclusion: The customized miniplate did not present better stress distribution than two commonly used types of fixation. Fixation with two straight miniplates, either with four or six holes, offers adequate resistance for 10 mm linear advancements.

1. Introduction

Bilateral sagittal split ramus osteotomy (SSRO), as described by Obwegeser and Dal-Pont (Trauner and Obwegeser, 1957, Dal Pont 1961), is now a standard, common, and successful procedure in oral and maxillofacial surgery for the treatment of certain mandibular discrepancies. In spite of the extensive use of SSRO, there is still controversy regarding the best method of fixation. Several clinical studies have found that three fixation methods — bicortical screws, miniplates, and hybrids — do not differ significantly from each other when comparing the amount of advancement with the amount of postsurgical instability, so their use is a matter of surgical choice (Blomqvist and Isaksson, 1994; Blomqvist et al., 1997). Large clinical studies have shown that one miniplate is sufficiently stable for mandibular advancement (Ozden et al., 2006; Sato et al., 2010; De Oliveira et al., 2016; Epker, 1977). However, there is a tendency for relapse if repositioning exceeds 7 mm (Joss

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and Vassalli, 2009) and in cases of counterclockwise rotation (De Oliveira et al., 2016; Nieblerová et al., 2012), which must be taken into account.

Clinically, it is difficult to measure the extent to which bone repair can be damaged by these differences in resistance among these three fixation techniques (Olivera et al., 2012). Finite element analysis (FEA) is a numerical method for addressing biomechanical issues, and a powerful research tool that can provide precise insight into the complex mechanical behavior of the mandible when affected by mechanical loading, which is still difficult to assess otherwise (Vollmer et al., 2000). Three-dimensional FEA illustrates stress behavior more realistically than the other methods when it comes to considering the complexities that characterize actual clinical conditions (Maurer et al., 1999; Erkmen et al., 2005a).

Based on the information obtained, and the lack of research evaluating SSRO with long advancements, the aim of this study was to compare, using FEA, the stress values for three different methods of internal fixation in terms of their ability to resist vertical loads, when used in SSRO with 10 mm advancements.

2. Materials and methods

2.1. Finite element model development and properties

In order to perform finite element analysis, it was first necessary to build the screws, miniplates, and geometric structures of a hemimandible. Initially the 3D model of the hemimandible was built by scanning a polyurethane jaw (Franceschi & Costa e Silva Ltda., Jaú, São Paulo, Brazil), after carrying out the SSRO.

After scanning, 3-matic Research 9.0 software (Materialise, Leuven, Belgium) was used to adjust the STL file and create the cortical and medullary bone. Then the miniplates and screws were made, and the models were finalized using SolidWorks 2010 software (SolidWorks, Concord, Massachusetts, USA). The designs for the titanium miniplate and screw models were based on physical specimens from Customize® (São Paulo, Brazil). In order to simplify the model, we eliminated the areas not relevant to the study of stress dissipation, such as the teeth. The 3D models generated were then imported into the CAE (computer-aided engineering) environment using ANSYS® Workbench™ 12 (Ansys Inc, Canonsburg, Pennsylvania, USA) for the finite element analysis.

Regarding the meshes generated for this study, the maximum size of the elements was limited to 0.5 mm. Consequently, the models had 1141936–1295884 elements, and 1737431–1981699 nodes (Table 1). The contact conditions were defined as attachment with screws/miniplates, screws/bone, and cortical bone/medullary bone. Miniplate/bone contacts and contacts between anterior and posterior segments were suppressed due to geometric limitations. The anterior segment was limited to three degrees of freedom (rotation on the *z*-axis and displacement on the *x*- and *y*-axes), and the mandible was locked (zero degrees of freedom) in the condyle, coronoid process, and insertion of the masseter muscle (positioned in the posterior lower region of the proximal segment). Loading was defined as a vertical 100 N force in the mid-line region (arrow), applied on the surface in red (Fig. 1).

The three types of fixation were divided into groups. The 3DCP group used a customized titanium miniplate — a new miniplate model that employs a combination of different structural shapes (meshes and grid miniplates), and is used for osteosynthesis in the field of oral and maxillofacial surgery. This was fixed using eight monocortical screws. The 4-H2P group used two conventional four-hole titanium miniplates secured with eight monocortical screws. The 6-H2P group used two conventional six-hole titanium miniplates with 12 monocortical screws. The materials used for the three techniques were from the 2.0 mm system, with 6 mm monocortical screws. Each miniplate was folded and/or made to be in perfect contact with the bone. SSRO was simulated according to Epker (1977), with 10 mm advancement between the proximal and distal segments. The two bone fragments were firmly fixed together, allowing only the displacement towards the chewing force.

3. Results

3.1. Finite element analysis

The FEA results were examined as follows: (1) qualitative and comparative analysis among the three groups, simulated by means of the figures, using color gradients based on the concentrations of stresses in each region; and (2) quantitative analysis using numerical readings for stresses at certain nodes of the model mesh. All analyses were performed whilst taking into account the von Misses stresses and modified von Misses stresses, as well as the maximum and minimum principal stresses, measured in megapascals (N/mm^2) and represented on a scale using color gradients.

For the evaluation of the 6-H2P group, it was observed that the fixation system allowed a displacement of 1.52 mm after loading, with a maximum principal stress (σ_{max}) located near the screw close to the osteotomy of the upper miniplate of the proximal segment. Stress was also observed in the region near the screw close to the osteotomy of the lower miniplate, but with less intensity. The stress was found to dissipated to the upper and posterior region of the segment, an area considered resistant due to its bone thickness (oblique line of the mandible). When analyzing the distal segment, the stress was found to be higher in the area near the screws close to the osteotomy than in the other regions, which showed only minimal stress in the surrounding bone (Fig. 2).

The minimum stress (σ_{min}) was −246.43 MPa. As for the titanium miniplate, this figure showed a conventional von Mises stress pattern (σ_{vm}) around the top of the upper miniplate near the screw closest to the proximal segment osteotomy, and a modified von Mises (σ_{mvm}) value of 210.66 MPa (Fig. 3) (Table 1).

In the evaluation of the 4-H2P group, the same characteristics of stress distribution as in the previous group were maintained, with a displacement of 1.62 mm, which was smaller than in the 3DCP group and bigger than in the 6-H2P group. The σ_{max} was detected in the bone near the screw close to the upper miniplate osteotomy of the proximal segment, as observed in the other groups (Fig. 4), but in this group the stress increased to 242.67 MPa, i.e., 41.12 MPa higher than in the 6-H2P group, and with a σ_{min} of −237.89 MPa. Evaluation of the titanium miniplate showed a conventional σ_{vm} pattern near the top of the upper miniplate near the screw closest to the proximal segment osteotomy, with 1005 MPa (Fig. 5), and a slight increase in σ_{vm} over the 3DCP group (Table 1).

Fig. 3 shows the 3DCP group, in which the displacement was 2.57 mm. The miniplate in this group had the highest stress of all groups, as well as a substantial concentration of stresses with high values in the upper region of the miniplate near the screw close to the osteotomy of the proximal segment (Fig. 6). In addition, its σ_{vm} value was 1580 MPa (Fig. 7), 50% higher than in the other groups tested. The value of σ_{max} for this group was 350.27 MPa, which was higher than the other two groups, but the distribution was maintained in the same area. Table 1 shows the observed σ_{mvm} of 374 MPa, which was also higher than for the 6-H2P and 4-H2P groups. The σ_{min} value was −234.44 MPa, which was close to the values for the other groups (Table 1).

4. Discussion

A literature search found no studies that had performed similar evaluations involving large mandibular advancements. The

Table 1
Quantitative analysis.

Groups	Bone stress (MPa)			Material stress (MPa)	Displacement (mm)	Mesh	
	Modified von Mises (max)	Max principal	Min principal	von Mises (max)		Knot	Elements
3DCP	374.49	350.27	−234.44	1580.4	2.57	1981699	1295884
4-H2P	256.1	242.67	−237.89	1005	1.62	1757431	1141936
6-H2P	210.66	201.55	−246.43	977.56	1.52	1940690	1272355

mm = millimeters.
MPa = megapascals

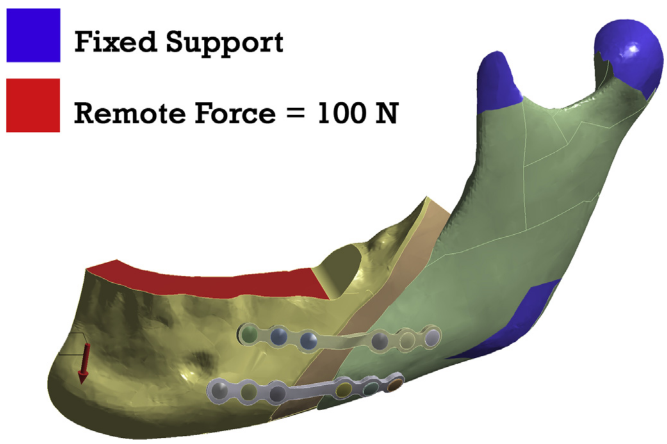

Fig. 1. Finite element models: locking areas (condyle, coronoid process, and insertion of masseter muscle) with 100 N loading in the midline region (arrow).

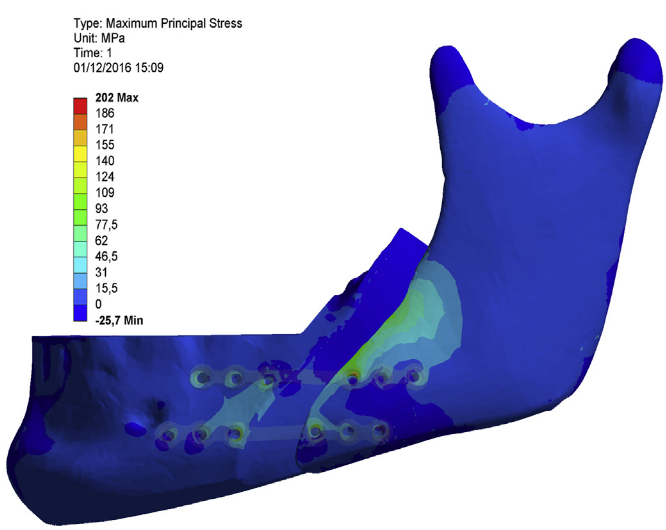

Fig. 2. Maximum Principal Stress values in 6-H2P group - stress dissipated to the oblique line of the mandible.

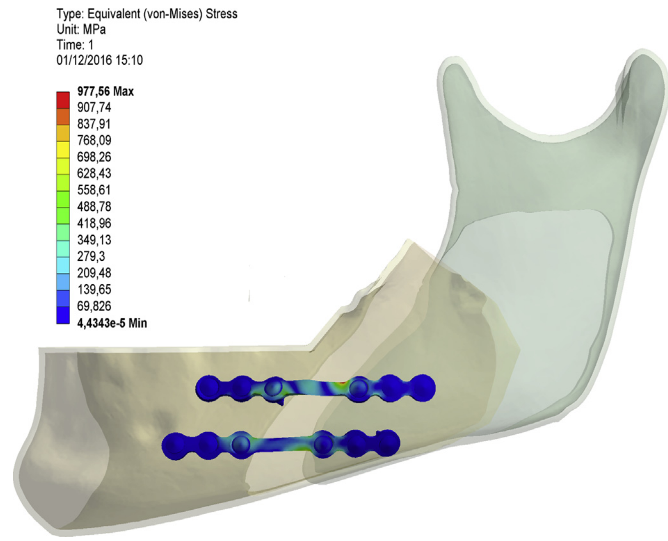

Fig. 3. Von-Mises Stress values in 6-H2P group - von Mises stress pattern around the top of the upper miniplate near the screw closest to the proximal segment osteotomy.

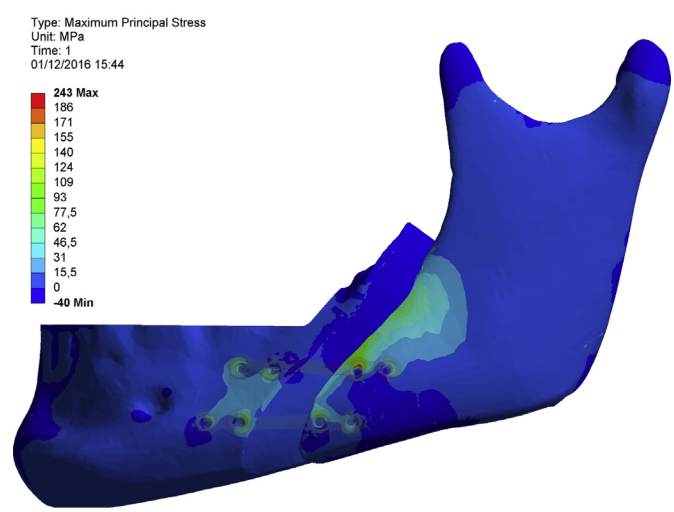

Fig. 4. Maximum Principal Stress values in 4-H2P group - stress dissipated to the oblique line of the mandible.

stability and resistance of fixations are important factors, and require attention. Most studies on SSRO have focused on surgery involving mandibular advancements of 5 mm (Erkmen et al., 2005a, 2005b; Pereira Filho et al., 2013; Sato et al., 2012a, 2012b;) or 7 mm (Joss and Vassalli, 2009; Aymach et al., 2011; Schwartz et al., 2016).

This study was the first to evaluate, by means of FEA, SSRO with 10 mm advancements, and showed that the customized miniplate allowed a larger displacement, generating higher stresses in both bone and metal, compared with the systems fixed using two separate miniplates. We attribute this result to the better distribution presented by separate miniplates positioned closer to the tension and compression zones, making those systems more resistant to linear displacement, thus reducing stress in the critical osteotomy regions.

The SSROs were stabilized using two fixation techniques commonly employed in long advancements that require more resistance, and a new technique using a customized miniplate model. Our evaluation showed that two straight miniplates with

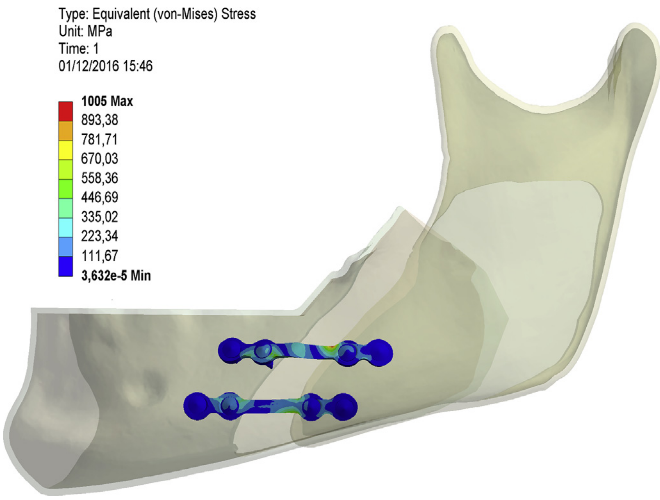

Fig. 5. Von-Mises Stress values in 4-H2P group – same characteristics of stress distribution as in the 6-H2P group.

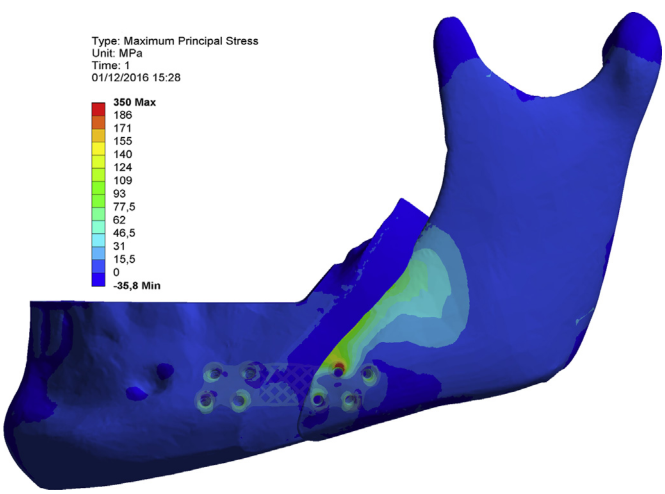

Fig. 6. Maximum Principal Stress values in 3DCP group.

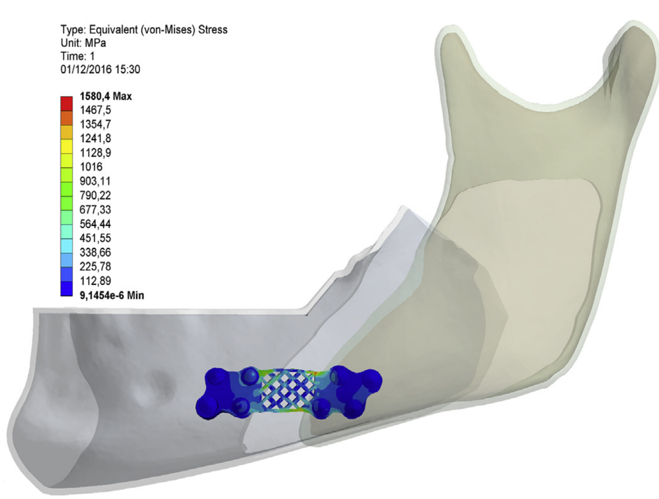

Fig. 7. Von-Mises Stress values in 3DCP group (red indicates areas of high stress concentration).

four or six holes showed less concentration of stress and less displacement than the new miniplate model, so we suggest customizing the system, but using the widely tested miniplate models, in this case the straight miniplates. Today's technology allows for the customization of any miniplate model, with changes to miniplate designs very easily made. However, before thinking about creating a new model, consideration must be given to the resistance required and whether the model meets the desired characteristics of stress distribution and resistance. This is especially the case when fixing osteotomies involving large mandibular advancements, where there is decreased bone contact and therefore the need for a more resistant system.

An ideal internal fixation method should obtain maximum rigidity between the segments while exerting minimum stress on the surrounding tissue, in order to allow proper healing. Excessive stress around fixative appliances can cause gradual resorption of the surrounding bone and loosening of the screws (Erkmen et al., 2005b; Sato et al., 2012a; Sigua-Rodriguez et al., 2018). Our evaluations showed that the highest stresses were generated in the areas close to the osteotomies, especially in the upper miniplate of the proximal segment, which is classified as a critical area. Our suggestion to surgeons (especially inexperienced surgeons learning these techniques) is to avoid unnecessary folds, especially in this location, which is a common clinical approach. This is an important point to consider in preventing miniplate fracture, or loss and/or loosening of the screws in the region.

Customization is becoming increasingly popular. It is a useful tool for the treatment of facial deformities and may be particularly appropriate in the following cases: 1) pronounced asymmetry with a substantial vertical component; 2) likely poor occlusal stability during the postoperative period, regardless of whether this is because of tooth loss or the use of a surgery-first approach; and 3) anatomical deformities or severe cases that are difficult to treat with conventional osteosynthesis systems (Brunso et al., 2016). This technology offers better predictability of results than conventional planning. Another feature that favors the use of customization is the possibility of manufacturing cutting and miniplate positioning guides, allowing the fixation of screws in areas of higher bone quality, so that the need to change its shape and original position due to loss of screw torque during installation is almost eliminated.

There are no explicit guidelines or suggestions in the literature regarding the type of stress that must be used in the calculations (principle stress and von Mises stress are equally used). Von Mises stress values are defined as the beginning of deformation for ductile materials, such as dental implants, and have already been used for tests on titanium screws and miniplates (Kilinç et al., 2016).Bone can be classified as brittle in an engineering sense; therefore, principal stress values are appropriate (Kilinç et al., 2016; Simşek et al., 2006). Our study maintained the same standards of evaluation used in previous research. The values obtained are important in interpreting stresses within fixation devices, and in measuring their possible effects.

In clinical situations with lower bone contact, when there is great muscle resistance or when the patient applies large chewing forces, in order to achieve maximum rigidity in the immediate mandibular function, techniques offering higher mechanical resistance are recommended, such as bicortical screws and hybrid techniques (Ochs, 2003; McHugh and Van Sickels, 2012). However, some cases present anatomical limitations, such as positioning of the teeth, location of the inferior alveolar nerve, thin alveolar walls after third molar extraction during sagittal osteotomy, minimal surface of overlap between distal and proximal segments, and incorrect fractures. Moreover, in many patients it is necessary to perform a secondary osteotomy of the distal segment, just behind the molar terminal, to help align the proximal and distal segments in a passive manner (Ellis, 2007). In these circumstances, the best approach is to use miniplates (Scheerlinck et al., 1994).

Our study evaluated two stable fixation techniques commonly used in the clinical setting of long advancements, ruling out bicortical screw evaluation. The authors found out that although the effectiveness of fixation stability using these techniques is known (Sato et al., 2012a; Gassmann et al., 1990), the circumstances mentioned above present limitations, which is why we do not recommend their use in cases of large and/or asymmetric advancements. However, the final decision is a judgment call, based on the clinical characteristics of each case, professional experience, and local availability of fixation materials.

5. Conclusion

Stress distribution in the customized miniplate was no better than in two types of commonly used fixation. The fixations using two straight miniplates, whether with four or six holes each, provide adequate resistance for 10 mm linear advancements, with less displacement.

Ethical approval

Not required.

Conflicts of interest

None declared.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jcms.2019.01.007.

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