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Biomechanical evaluation of stability after mandibular sagittal split osteotomy for advancement by Obwegeser–Dal Pont and Puricelli techniques using three-dimensional finite elements

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Abstract

Background The surgical treatment for mandibular repositioning using a bilateral sagittal split osteotomy (BSSO) favours the development of techniques that result in adequate repair and stability. In Puricelli's mandibular sagittal split osteotomy (PMSSO) proposal, the vertical lateral cut osteotomy is located in the interradicular space between the lower first molar and second premolar.

Objectives This in silico study aimed to investigate the mechanical stability of PMSSO and compare it with the classical Obwegeser–Dal Pont technique for mandibular advancement.

Materials and methods A computational geometric model of the mandible was created in a virtual environment using computer-aided design (CAD) software. After reproducing the advancements, two test groups were developed: GTOD10, Obwegeser–Dal Pont osteotomy, and GTP10, Puricelli osteotomy, both simulating a 10-mm mandibular advancement, allowing for measuring the area of overlap between bone segments. With the geometric changes promoted by the osteotomy, boundary conditions of displacement and force were applied to a CAD software based on finite element analysis (FEA), allowing for quantitative and comparative analysis of the stress and vertical displacement of the mandible, mechanical measurements that may be associated with strength and stiffness.

Results A 17.48% higher stress was observed in the GTP10 group than in GTOD10. However, the region of highest stress in GTP10 was found in a part of the bone that was still intact and far from the area of fragility caused by lateral vertical osteotomy. In contrast, in GTOD10, the region with high stress was in a less resistant bone region. The GTP10 group showed a 28.73% lower displacement than GTOD10. The area of overlap between the proximal and distal segments of the mandible was 33.13% larger in the GTP10 than in the GTOD10 group.

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Conclusion The PMSSO method, performed in large mandibular advancements, keeps the point of highest stress away from the mandibular fragility zone. Considering the same amount of advancement, it also promotes less displacement and larger areas of bone overlap.

Clinical relevance The results suggest that PMSSO, applied in large mandibular advancement, presents greater postoperative stability.

Keywords Mandibular advancement, Orthognathic surgery, Mechanical stability, Finite element analysis (FEA), Obwegeser–Dal Pont (BSSO), Puricelli osteotomy (PMSSO)

Introduction

An intraoral technique composed of unilateral (SSO) or bilateral (BSSO) sagittal split osteotomy, as described by Obwegeser in 1957 [1, 2], remains in wide use and indications. In 1961, Dal Pont incorporated a retromolar osteotomy into the Obwegeser technique, resulting in less displacement of the proximal segment due to muscle activity [3]. Since BSSO is widely used to treat different mandibular bone deformities, several variations have been described based on the preferences and experience of surgeons [4]. From a biomechanical point of view, there is still no consensus on the best location of the lateral osteotomy cut during BSSO [4–6]. Puricelli's mandibular sagittal split osteotomy [6, 7] involves a vertical, lateral cut osteotomy located from the interradicular space between the first molar and second premolar in a vertical direction to the base in the body of the mandible, with maximum proximity to the mental foramen hole of 3 mm. This proposal allows for greater movement between bone segments. It creates a larger area of overlap between medullary bone surfaces, facilitating the use of fixation systems and allowing the simultaneous extraction of third molars.

The in silico finite element analysis (FEA) obtained with computer-aided design (CAD) software can represent a real situation with fidelity, reducing the need to build prototypes, has a lower cost, and generates faster results than mechanical tests. The error rate generated by numerical interpretations is minimal, especially when meshes are well simulated and analysed. Using FEA to evaluate BSSO results through a numerical model allows us to computationally simulate the mandibular biomechanical behaviour [8, 9]. The method is suitable for complex geometries as an interesting, non-invasive tool capable of providing reliable qualitative and quantitative evaluations. Although widely used in the evaluation of biomechanical systems involving bone tissue, the use of the method in major mandibular advances is limited in the literature. Thus, this study analysed and compared, through FEA, the mechanical stability resulting from the Obwegeser–Dal Pont and Puricelli osteotomies in large mandibular advancements from the point of view of the distribution of stress in the mandible and vertical displacement. Additionally, the area of bone overlap can be determined as the first step in the FEA analysis, which involves developing a geometric model of the mandible that undergoes the osteotomy using CAD software.

Materials and methods

The present descriptive/comparative study used FEA and was developed in a virtual environment. The study was carried out at the School of Dentistry in cooperation with the Applied Mechanics Group of the Department of Mechanical Engineering, both at the Federal University of Rio Grande do Sul (UFRGS).

The research was carried out in three stages:

- Pre-processing: development of a computational geometric model using CAD software.
- Processing: using FEA with CAD.
- Post-processing: analysis of the results.

A mandibular geometric model was developed to reproduce the mechanical conditions found in vivo in the Obwegeser–Dal Pont and Puricelli osteotomies. Geometric modifications were done on a geometric model to simulate osteotomy using two BSSO techniques. These modifications allowed for the repositioning of the sectioned mandible. Additionally, components were included in the geometry to simulate the fixation process with plates and screws, which were simulated as simple cylinders with the appropriate length for monocortical penetration and fixation of mini plates. These modifications were performed in the geometric model of the mandible published by Amorm Vasco et al. (2016) [10]. Tissues not relevant to the study, such as teeth, were removed.

The necessary geometric changes were made in CAD software. Manipulations were performed on the three-dimensional model of the mandible to simulate BSSO according to the two experimental groups. The groups defined after the reproduction of the planned movements were GTOD10 (Obwegeser–Dal Pont osteotomy) and GTP10 (Puricelli osteotomy); both used 10 mm advancements (Fig. 1). For segmentation, the thickness of the cut was 1 mm. Because the osteotomy was performed in a curved region and the mandible has a U shape, in the 10 mm advancements, an angulation of 10 degrees was

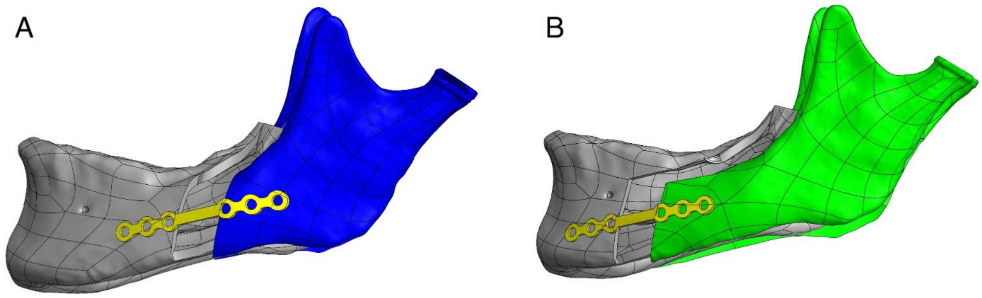

Fig. 1 Representation of the experimental groups. (**A**) GTOD10, Obwegeser–Dal Pont mandibular osteotomy with 10 mm advancement. (**B**) GTP10, Puricelli mandibular osteotomy with 10 mm advancement

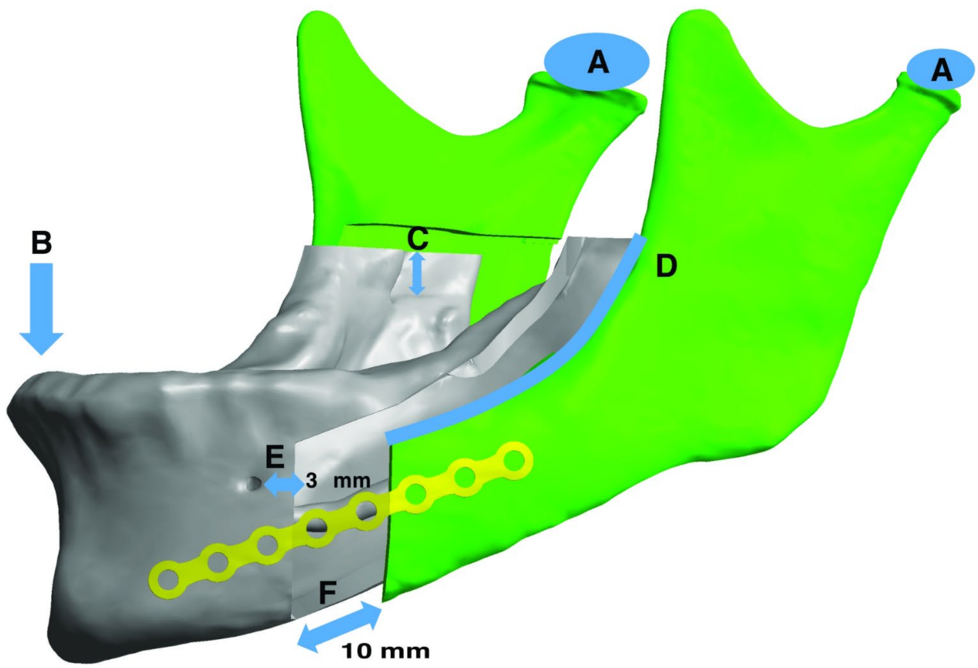

Fig. 2 A BSSO (bilateral) model is presented for graphical location of the osteotomy, GTP10 group. Gray represents the distal mandibular body, and green the proximal segment. (**A**) Mandible fixed (at zero degrees of freedom) to the condyle. (**B**) The application of force (1 N) to the mandibular midline in the vertical direction. (**C**) The first osteotomy was performed at 13 mm from the mandibular notch. (**D**) The second osteotomy was parallel to the external oblique line and 5 mm lingual to it. (**E**) The third osteotomy was 3 mm proximal to the distal border of the mental foramen. (**F**) The gap corresponds to 10 mm of advancement in the mandibular body

allowed in the horizontal axis. This prevented any interference or contact with the bone, which could cause a residual stress effect. For comparative purposes, only one plate was used in each study, as proposed by the original techniques.

In the GTOD10 group, the procedure was performed perpendicular to the axis of the mandibular ramus, with the first osteotomy performed at 13 mm from the mandibular notch, the second parallel to the external oblique line and 5 mm lingual to it, and the third osteotomy, 23 mm proximal to the distal border of the mental foramen. The proximal and distal stumps were spaced 10 mm, simulating mandibular advancement.

In the GTP10 group, the procedure was performed perpendicular to the axis of the mandibular ramus, with the first and second osteotomies performed as described above, but with the third osteotomy 3 mm proximal to the distal border of the mental foramen (i.e., anterior by 20 mm). The proximal and distal stumps were spaced 10 mm, simulating mandibular advancement.

Osteotomies and advancements were performed bilaterally (Fig. 2). The segments were fixed with the 2.0 system. In both groups, 6-hole monocortical plates with space and six 5-mm screws were used. The screws were simulated as simple cylinders, with the appropriate length for monocortical penetration and fixation of mini plates. A perfect fit between the plate hole and the screw, as well as between the screws and the bone, was assumed, with no slippage at this interface [11]. Fasteners, mini plates, and screws were not detailed in this study [12], and a geometric simplification in the contact of these structures was applied [12, 13].

Once the geometries of the groups were defined, finite element models were developed. To compare the techniques studied, all geometric shapes were considered homogeneous, isotropic, and elastic-linear [1, 6, 14–18]. After performing a sensitivity study of the finite element mesh, 358,179 and 404,760 mesh elements were used in GTOD10 and GTP10, respectively. The properties of the materials were considered according to Puricelli et al. (2007) [12] and Chang et al. (2019) [13]. Young's modulus for bone was 17 GPa and 110 GPa for plates and screws, with a Poisson's ratio of 0.3 in both cases.

In the finite element model, in both groups, the mandible was fixed in the condyles, and a 1 N load was applied with a vertical force vector and perpendicular to the occlusal plane in the anterior corresponding region of the left hemimandible (Fig. 2). This condition allows a comparative analysis to be made between the different case studies. Different forces would cause a change in results proportional to the load ratio since the finite element model is linear. The model was constructed by applying symmetrical conditions in the plane, simulating only the left-sided hemimandible. The FEA simulation provided the distribution of the von Mises equivalent stress, allowing the identification of the zones of highest stress in the numerical model. The projected surface between the proximal and distal bone segments, measured in mm^2, was also evaluated to measure the overlapping area between the bone segments.

Results

After conducting the finite element analysis, the results were post-processed to allow for quantitative and comparative analyses of mandibular stress and vertical displacement of the mandible. Stress is a mechanical measure that may indicate the strength of a component or biomechanical system, whereas displacement may indicate the system's stiffness and stability. CAD post-processing allowed us to determine the overlapping area between bone segments of both groups. It should be noted that the results are based on a unit force (1 N). The results must be multiplied by the force ratio if a greater force is used since the finite element model is linear. For instance, if a force of 100 N is applied, the results must be multiplied by 100.

Mandibular stress

Numerical analysis showed that the maximum von Mises stress was 0.45897 MPa for the GTOD10 group and 0.55623 MPa for the GTP10 group. The stress distribution in both groups is presented in Fig. 3, with a colour gradient showing the variation in the regions of interest in this study.

Vertical displacement in the hemimandible

After applying the load to the anterior region of the left mandible (Fig. 4), the displacements observed were −0.095858 mm in the GTOD10 group and −0.068314 mm in the GTP10 group.

Bone overlap area between the segments

Analysis of the CAD showed that the projected area between the proximal and distal bone segments was 512.83 mm^2 and 767.00 mm^2 in the GTOD10 and GTP10 groups, respectively (Fig. 5).

Discussion

Biomodels of vital structures of the human body are widely used in research. Analysing these biomodels by finite elements reduces time and cost compared to other studies. It provides predictions that can aid in choosing the best technique for each mechanical and physiological requirement. In addition, it does not involve ethical issues or the need for clinical intervention [4, 9, 12, 19, 20]. The validation of mandibular biomodels and their finite element analysis has already been performed, showing a correlation coefficient of 0.992 [9].

In Puricelli osteotomy, the increase in the area of the proximal segment and the consequent decrease in the

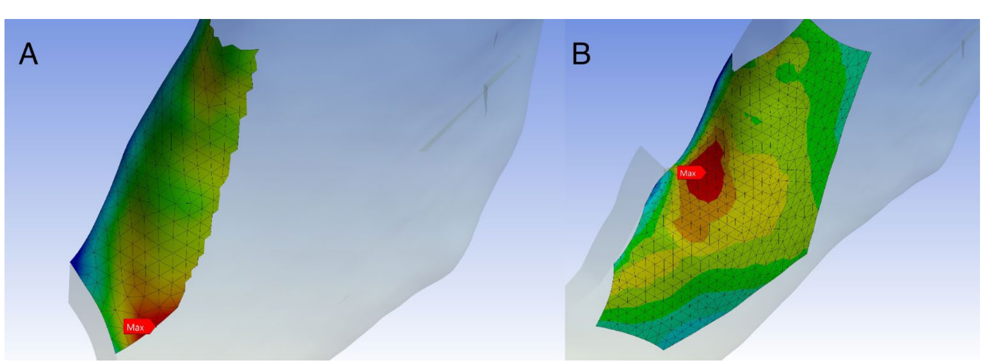

Fig. 3 Representation of stress distribution, represented by the colour gradient, in the hemimandibles of the experimental groups. (**A**) GTOD10. (**B**) GTP10. The red arrows indicate the maximum stress point

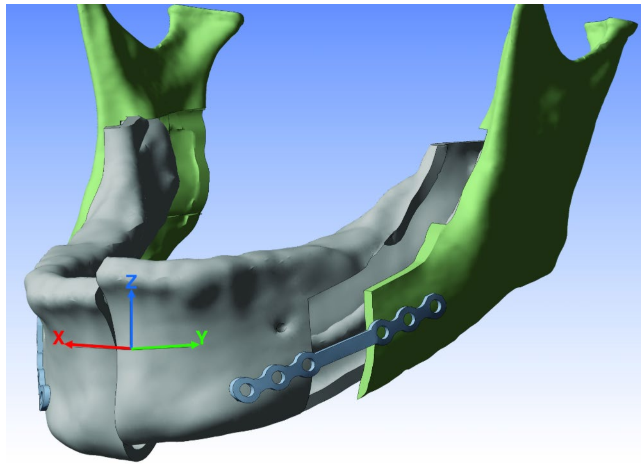

Fig. 4 Representation of the vertical displacement of the hemimandible in the GTP10, compared to the mirrored undeformed version. A scale factor was used for the deformed version

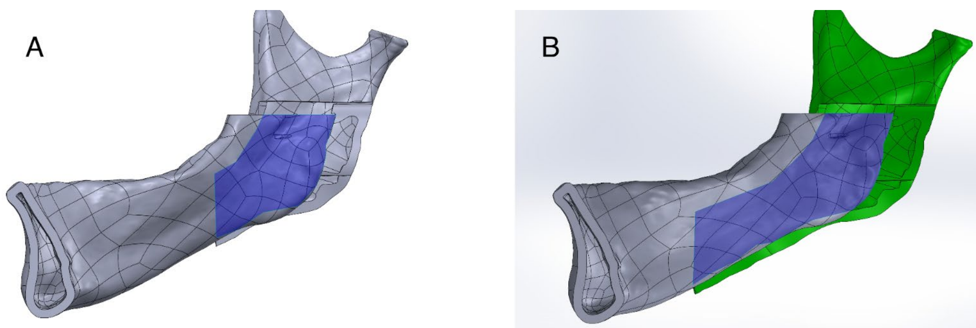

Fig. 5 Representation of the areas of bone overlap in the two experimental groups (area delimited by the blue line). (**A**) GTOD10. (**B**) GTP10

lever arm applied to the mandible provide lower values of stress and displacements. The magnitude of the displacements indicates mandible stability; thus, lower values indicate greater stability of the bone segments. It is suggested that, in vivo, there is greater stability, with a decrease in the lever arm, resulting in better repair, decreased displacement due to muscle activity, and, consequently, a reduction in the period of elastic intermaxillary immobilisation [6, 12].

This study used FEA to compare the Obwegeser–Dal Pont and Puricelli techniques for mandibular advancements. A previous study evaluating mandibular osteotomies without segment displacement showed that the Puricelli technique results in lower stress and displacement values compared to the classical technique of Obwegeser–Dal Pont [12].

The present study was based on the geometric model published by Amorim Vasco et al. (2016) [10], and the properties of the materials were based on the studies by Puricelli et al. (2007) and Chang et al. (2019) [12, 13]. A virtual model of the hemimandible was used for a comparative analysis, with a unitary force (1 N) applied in the anterior region of the left hemimandible and stabilisation performed in the left mandibular condyle region [21]. Since the FEA was based on a linear model, these qualitative results are valid for other loads. As it was not the object of this study, the effect of contact stresses at the interface between the plate and the mandible was not evaluated [12].

FEA of mandibular stability in mandibular advancements ranging from 3 mm to 10 mm have been reported but not associated with Puricelli's mandibular osteotomy [14–16, 21–25]. Mandibular advancements of 10 mm or more are considered 'major advancements' and present a higher tendency for relapse [17, 26, 27].

In this study, the 10 mm mandibular advancement is justified given the increasing indication of BSSO for treating patients with large skeletal discrepancies and obstructive sleep apnea-hypopnea syndrome (OSAHS). Great mandibular advancements increase the pharyngeal airspace with distension of the velopharyngeal and suprahyoid muscles, benefiting patients with OSAHS [28] and increasing the effectiveness of surgical treatments [29].

The Puricelli technique resulted in a 17.48% higher mandibular stress than the Obwegeser–Dal Pont approach. In the comparison of osteotomy methods, the point of greatest stress is distant from the area of fragility resulting from vertical osteotomy and the region of fixation of the osteosynthesis media (plates and screws), thus suggesting greater stability after Puricelli osteotomy. In the evaluation of the hemimandible displacement, it was observed that Obwegeser–Dal Pont osteotomy resulted in a displacement 40.32% greater than the Puricelli technique.

The system of third-class levers can be applied in interpreting the stress and displacement evaluation [4, 30]. The temporomandibular joint represents the fulcrum, and the application of force to the anterior region of the hemimandible represents a force vector. In comparing 10 mm mandibular advancements, the more anterior the vertical line of the mandibular osteotomy is performed, the greater the distance from the high-stress area and the smaller the displacement. The anteriorisation of the vertical osteotomy of the mandible ensures greater stability [18], unlike the vertical osteotomy in the classic Obwegeser–Dal Pont technique, which is performed near the region of greater mandibular fragility (mandibular angle) [31].

Considering the area of overlap between the proximal and distal segments of the mandible, the results of the GTP10 group show an area 33.13% larger than the GTOD10 group. The maximisation of the overlapping area indicates the greatest possibility of contact and is related to the surgical technique employed [29]. In mandibular osteotomies, there is no treatment on the bone surfaces and the gap to guide bone neoformation. The bone repair depends on the space between the osteotomy lines, anatomical location, mechanical/muscular forces at this site, and the patient's age and systemic condition [32–34]. The larger area of overlap between the osteotomised segments and the anteriorisation of the vertical line of osteotomy, observed in Puricelli's mandibular osteotomy, results in an increase in the area of medullary exposure and in the organisation of a clot, consequently favouring bone neoformation. The larger extension of the overlapping surface shows a significant association with the decrease in the mean or maximum stress value [35]. In addition, the smaller the contact surface, the greater the risk of postoperative fracture [29].

The condition of greater sliding of the segment corresponding to the body of the mandible, offered by the Puricelli technique, allows for an average 18 mm increase in the proposal of advancement. Even in the acute traction and stretching of the inserted muscles and the mucosa, vascularisation is not affected when properly handled.

Conclusions

Using FEA, this study demonstrates that PMSSO, used in large mandibular advancements, results in the location of critical (maximum) stress away from the vertical osteotomy line, less vertical displacement of the mandible, and greater area of overlap between bone segments, thus suggesting greater mechanical stability.

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Author contributions
Vinícius Matheus Szydloski conducted the study as his M.Sc. dissertation, participating in every stage of the project. Jakson Manfredini Vassoler, João Vitor Saggin Bordin and Ana Bárbara Krummenauer Formenton contributed to study design, analysis, manuscript writing and revision. Mauro Gomes Trein Leite, Renan Langie and Alexandre Silva de Quevedo contributed to manuscript writing and revision. Edela Puricelli supervised the study and contributed to study design, manuscript writing and revision. Deise Ponzoni conducted the project, supervised the study and contributed to study design, manuscript writing and revision.

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Data availability
The data supporting the findings of this research can be obtained directly from the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Informed consent
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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