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Assessment of Three Bilateral Sagittal Split Osteotomy Techniques with Respect to Mandibular Biomechanical Stability by Experimental Study and Finite Element Analysis Simulation

Hiromasa TAKAHASHI(1), Haruhiko FURUTA(1), Shigeaki MORIYAMA(2),
Yuki SAKAMOTO(2), Hisao MATSUNAGA(2) and Toshihiro KIKUTA(1)

(1) *Department of Oral and Maxillofacial Surgery, Faculty of Medicine, Fukuoka University*
(2) *Department of Mechanical Engineering, Faculty of Engineering, Fukuoka University*

Abstract：*Background*：No consensus has been reached on the ideal location for the lateral osteotomy cut in bilateral sagittal split osteotomy (BSSO) from the perspective of biomechanics. We assessed three BSSO techniques concerning mandibular biomechanical stability with experimental study and finite element analysis (FEA) simulation, and compared the study types. Methods：In the experimental study, 30 polyurethane-based synthetic mandibles were used. Pairs of model sets ($n=5$ models/set) were processed by using any of the following techniques：⑴ Trauner-Obwegeser (TO) method, ⑵ Obwegeser original (Ob) method, and ⑶ Obwegeser-Dal Pont (OD) method. In all methods, the distal segments were advanced by 5 mm parallel to the occlusal plane, and then reconstructed with bilateral titanium plates along Champy's line. All models were exposed to compression loads of up to 70 N at the central incisors and right first molars. In the FEA simulation, a 3-D FEA model was constructed from computed tomography (CT) data, and osteotomy was simulated by using any of the three BSSO techniques. A compressive load (10-70 N with 10-N increments) was applied to the central incisors and right first molar perpendicular to the occlusal plane. In both studies, central incisor and right first molar displacements on loading were used to assess mechanical stability after BSSO. Additionally, the differences in mechanical stresses developing in the right screw-plating system were examined. *Results*：Under every magnitude of incisal and molar loading, the OD method showed the least displacement；the results of both study types were in good agreement. In the FEA simulation, under 70-N incisal and molar loading, the OD method showed the least von Mieses stress in the screw-plating system. *Conclusions*：The OD method results in greater mechanical stability than the other two techniques. FEA is a useful method for estimating mandibular stability.

Key words：**Finite element analysis；Bilateral sagittal split osteotomy；Biomechanical stability；Champy's lines of ideal osteosynthesis**

Introduction

Currently, bilateral sagittal split osteotomy (BSSO) is the most commonly performed orthognathic surgical procedure.(1) However, the location for the lateral osteotomy cut during BSSO varies according to the surgeon's preference, and no consensus has been reached on the ideal location from the perspective of biomechanics. Although biomechanics is only one of the factors determining the osteotomy technique to be used, it is important for the surgeon to consider the presence of jaw deformities while planning the treatment strategy.

Correspondence to：Hiromasa TAKAHASHI, DDS
Department of Oral and Maxillofacial Surgery, Faculty of Medicine, Fukuoka University 7-45-1, Nanakuma, Johnanku, Fukuoka 814-0180 Japan
Tel：(092)-801-1011 ext. 3535 Fax：(092)-801-1044 E-mail：hiromasatakahashi@gmail.com

Bilateral positional screws in an inverted-L pattern have become the gold standard for comparison of the various fixation techniques.[2] Although numerous studies have been conducted to compare the different types of fixation techniques, experiments comparing different BSSO techniques are limited.

Engineers and researchers in the field of solids mechanics currently use finite element analysis (FEA) simulation to study models.[3] Several authors have reported on the accuracy of FEA for describing the biomechanical behavior of bony specimens.[4)–6] Vollmer et al.[7] have found quite a high correlation between FEA simulation and *in vivo* measurements on mandibular specimens(correlation coefficient=0.992).

The aim of this study was to assess three BSSO techniques from the viewpoint of mandibular biomechanical stability by experimental study and FEA simulation, and to compare both types of study.

Materials and methods

Experimental study

Thirty polyurethane-based synthetic mandibles (8596 ; Synbone, Malans, Switzerland) were used in this study. The polyurethane replicas have been created from exactly matched human anatomy in all dimensions and proportions.[8] The internal-fixation devices tested were four-hole, straight titanium miniplates (447-224 ; Synthes Maxillofacial, West Chester, PA) of 1.0-mm thickness and titanium monocortical screws (401-846 ; Synthes Maxillofacial) of 2.0-mm outer thread diameter and 6.0-mm length.

Model preparation

The three BSSO techniques were performed by a single investigator (Figure 1). For each technique, pairs of model sets (n=5 models/set) were

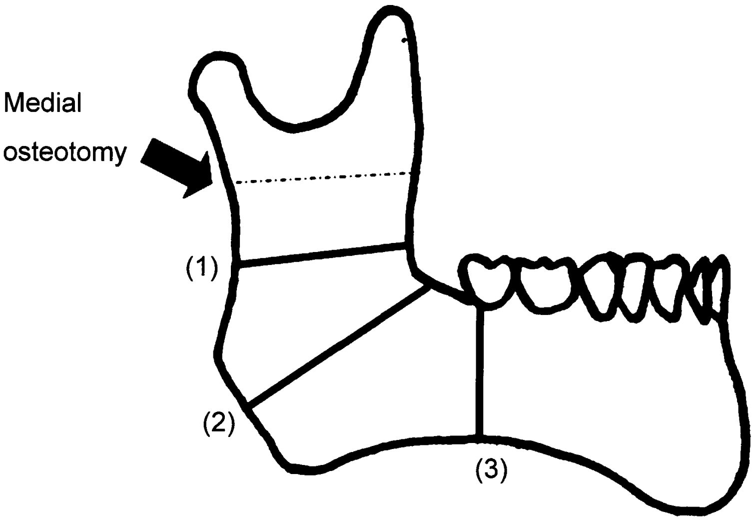

Figure 1 Schematic of the osteotomy lines in the three bilateral sagittal split osteotomy (BSSO) techniques : ⑴ Trauner-Obwegeser (TO) method, ⑵ Obwegeser original(Ob)method, and ⑶ Obwegeser-Dal Pont (OD) method

Figure 2 The experimental models after bilateral sagittal split osteotomy (BSSO) : ⑴ Trauner-Obwegeser (TO) method, ⑵ Obwegeser original (Ob) method, and ⑶ Obwegeser-Dal Pont (OD) method

prepared for incisal and molar loading such that only one test was performed on each model.

In all the three techniques, the osteotomy was performed with a Stryker TPS reciprocation saw (Stryker Instruments, Kalamazoo, MI). The distal segments were advanced by 5 mm parallel to the occlusal plane, and then reconstructed with bilateral monocortical titanium miniplate fixation with four screws per plate along Champy's line of ideal osteosynthesis.9) The plates were bent and adapted as far as possible to fit the bone contour (Figure 2). All models were uniformly prepared by placing 4-mm holes in the coronoid region using a standardized jig created from dental stone, similar to that described by Peterson.2) A stainless steel rod of 4-mm diameter was inserted into the holes.

The BSSO techniques

Mandibular biomechanical stability was compared among three BSSO techniques. In the Trauner-Obwegeser (TO) method, the lateral osteotomy cut was made horizontally from the distal region of the second molar to the posterior border well above the mandibular angle. This osteotomy technique was first performed in 1955,10) and published in English in 1957.11)

In the Obwegeser original (Ob) method, the lateral osteotomy cut was made from the distal region of the second molar to the midpoint of the mandibular angle. This osteotomy technique was first performed in 1957.10)

In the Obwegeser-Dal Pont (OD) method, the lateral osteotomy cut was made vertically from the distal of second molar to the lower border of the ascending ramus. This osteotomy technique was first performed in 1958,10) and published in English in 1961.12)

Constraints

Each model was placed on a custom-fabricated jig (Figure 3), similar to that described by Dichard.13) The temporomandibular joints were bilaterally constrained by the metallic plate of the jig, and the aforementioned stainless steel rod provided resistance to proximal segment rotation.

Loading

Biomechanical testing was carried out by using an electronic universal testing machine (EZ-Test ; Shimadzu, Kyoto, Japan ; Figure 4). The machine's 500-N compressive load cell measured ap-

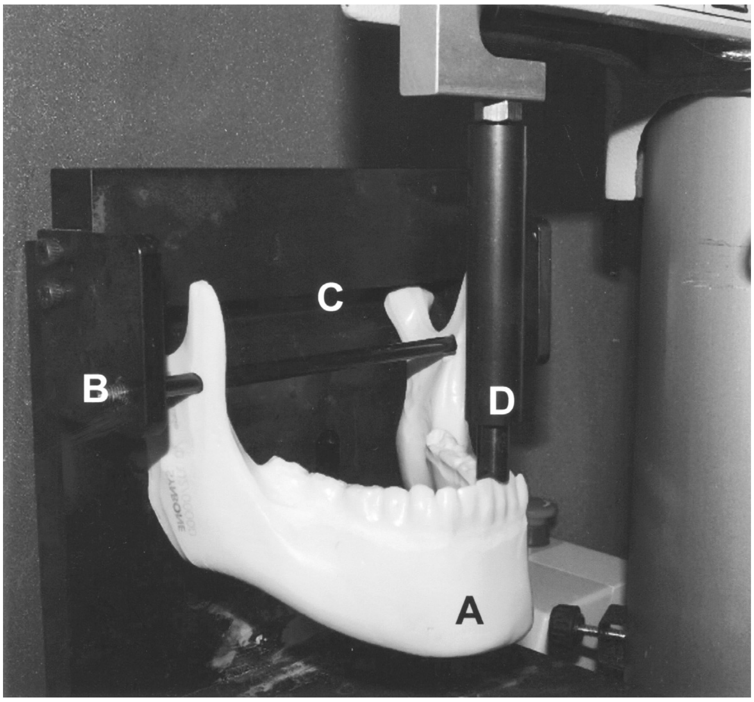

Figure 3 Experimental study setup : (A) Mandible, (B) stainless steel rod, (C) fixed plate for temporomandibular joint constraint, and (D) rod for loading compressive stress

plied force, and it exposed the models to compression loads of up to 70 N. Data were collected at 3 Hz and stored in the Trapezium software (Shimadzu).

All models in the incisal loading test (N=15) were loaded on the central incisors with a reverse roof-type tipped, custom-fabricated stainless steel rod of 5-mm diameter at a rate of 2.0 mm/min. All models in the molar loading test (N=15) were loaded on the right first molar with a round-tipped, custom-fabricated stainless steel rod of 5-mm diameter at a rate of 2.0 mm/min.

Central incisor displacement on incisal loading and right first molar displacement on molar loading were used to assess the mechanical stability after BSSO.

Statistical analyses

The data are described as the mean and standard deviation. The statistical significance of the results of the three techniques was determined by one-way analysis of variance (ANOVA) followed by Scheffe's F test.

FEA simulation

Mandibular modeling

We performed a computed tomography (CT) scan (Aquillion 64DAS TSX-1014/HA ; Toshiba Medical Systems, Tokyo, Japan) on a synthetic mandible model, and constructed a 3-D FEA model (Figure 5) from 0.5-mm serial axial sections apart from the 2-D CT image. The model consisted of

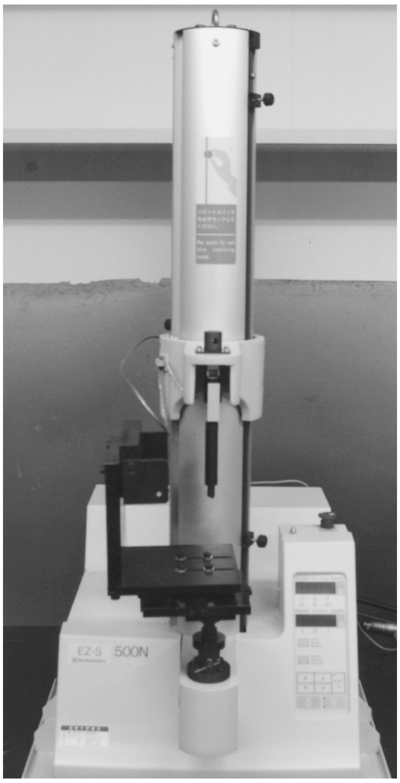

Figure 4 The electronic universal testing machine (EZ-Test ; Shimadzu, Kyoto, Japan)

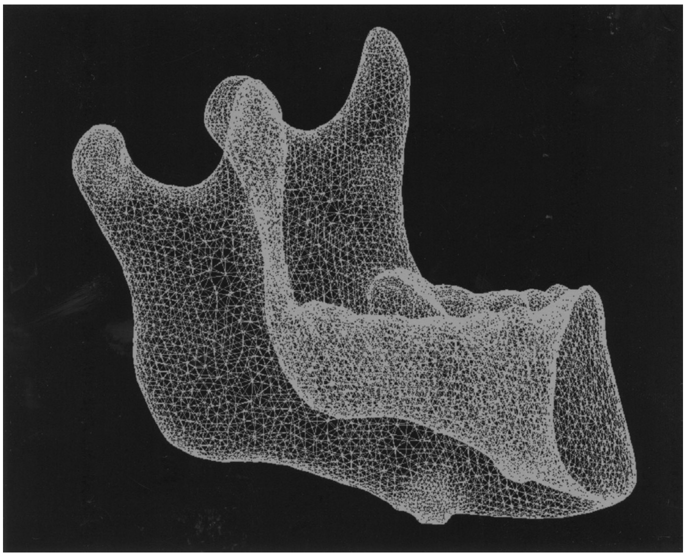

Figure 5 Three-dimensional finite element analysis (FEA)-simulated model of the mandible after bilateral sagittal split osteotomy (BSSO)

134,836 elements and 29,582 nodes. For simplification, bone was assumed to be a single homogenous phase. The material properties were defined as Young's modulus of 13.7 GPa and Poisson's ratio of 0.3, using previously reported data.14) We then simulated the osteotomy on the model by using any of the three BSSO techniques. All models assumed perfect slippage at the bone interfaces. All surgical simulations and analyses were performed using Mechanical Finder version 6.0 (Research Center Computational Mechanics, Tokyo, Japan).

Plate and screw modeling

Each model was stabilized following the simulated osteotomy by using miniplates and screws along Champy's lines as in the experimental study (Figure 6). However, the miniplates were not bent to fit the bone surface. The titanium miniplates were simulated as per the previously indicated physical specifications with the 3-D computer-aided design (3DCAD) software Solidworks2008 (Solidworks, Tokyo, Japan). The screws were simulated as simple 2.0-mm cylinders of length appropriate for monocortical penetration and fixation of the miniplates. The titanium plates and screws (Figure 7) were modeled with Young's modulus of 120 GPa and Poisson's ratio of 0.36, using previously reported data.14)

Constraints

The bilateral temporomandibular joints were completely constrained (Figure 8).

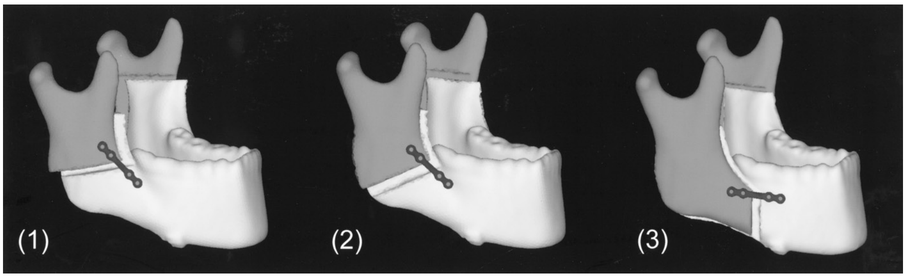

Figure 6 Finite element analysis (FEA)-simulated models after plate fixation

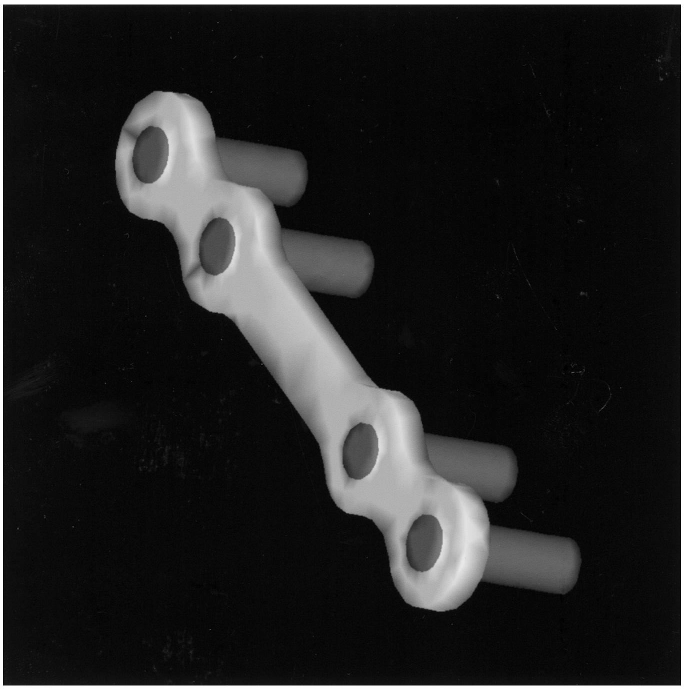

Figure 7 Three-dimensional finite element analysis(FEA)-simulated model of the titanium miniplate and screw

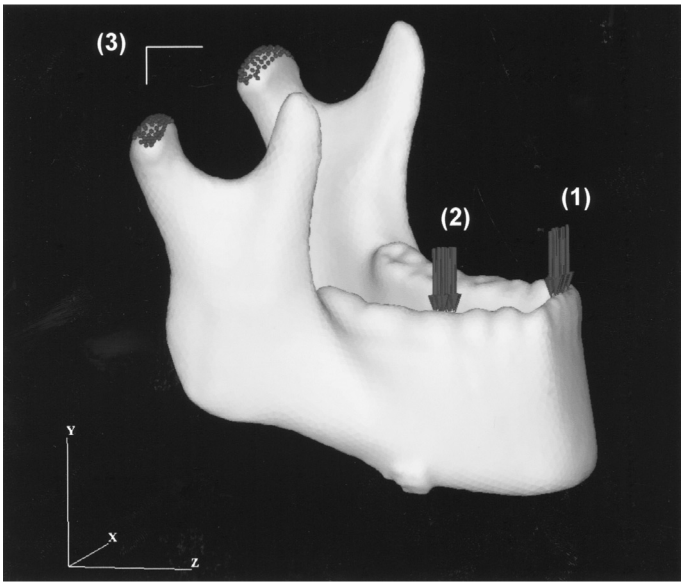

Figure 8 Establishment of constraints and loading in the finite element analysis (FEA) simulation:⑴ Incisal loading, ⑵ molar loading, and ⑶ constraints

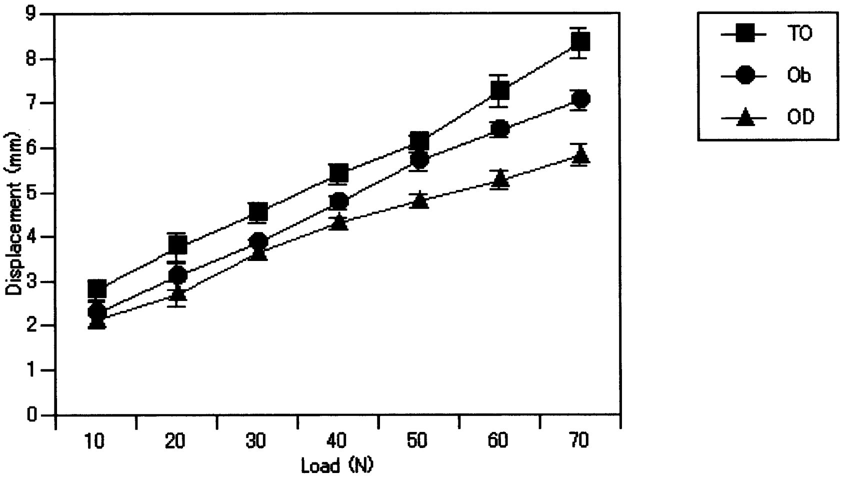

Figure 9 The load–displacement curves on incisal loading in the experimental study

Loading

We examined these models under two different loads similar to the experimental study (Figure 8). For incisal loading, a compressive load was applied to the central incisors perpendicular to the occlusal plane. For molar loading, a compressive load was applied to the right first molar perpendicular to the occlusal plane. For both tests, we set the magnitude of the vertical load at 10–70 N with 10–N increments.

Central incisor displacement on incisal loading and right first molar displacement on molar loading were used to assess the mechanical stability after BSSO. Additionally, we examined the differences in the mechanical stresses developing in the right screw–plating system.

Results

Experimental study

The load–displacement curves on incisal loading are shown in Figure 9. At every loading, the OD method showed the least displacement whereas the TO method showed the greatest displacement of the incisors. Significant differences were seen at every loading (Table 1).

Table 1 Comparisons of central incisor displacements on incisal loading in the experimental study

	TO	Ob	OD	Statistically Significant Difference	Between Groups and P Value
10N	2.82±0.22	2.25±0.28	2.14±0.20	Yes	OD and TO .0027 Ob and TO .0002
20N	3.76±0.31	3.11±0.30	2.70±0.29	Yes	OD and TO .0005 Ob and TO .0172
30N	4.54±0.24	3.87±0.07	3.63±0.14	Yes	OD and TO <.0001 Ob and TO .0001
40N	5.38±0.23	4.75±0.15	4.30±0.13	Yes	OD and Ob .0044 OD and TO <.0001 Ob and TO .0004
50N	6.12±0.16	5.68±0.21	4.80±0.16	Yes	OD and Ob <.0001 OD and TO <.0001 Ob and TO .0083
60N	7.25±0.35	6.38±0.18	5.26±0.22	Yes	OD and Ob <.0001 OD and TO <.0001 Ob and TO .0008
70N	8.32±0.34	7.04±0.22	5.82±0.25	Yes	OD and Ob <.0001 OD and TO <.0001 Ob and TO <.0001

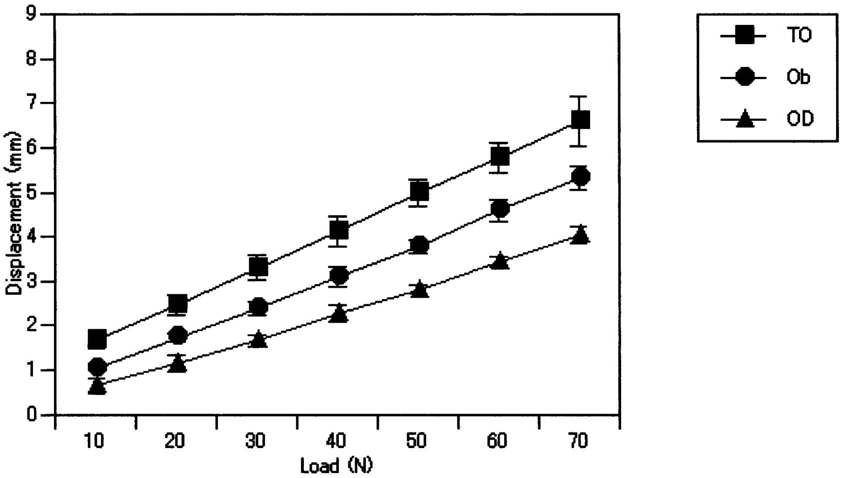

Figure 10 The load-displacement curves on molar loading in the experimental study

The load-displacement curves on molar loading are shown in Figure 10. At every loading, the OD method showed the least displacement whereas the TO method showed the most displacement of the right first molars. Significant differences were seen at every loading (Table 2).

FEA simulation

The load-displacement curves on incisal loading are shown in Figure 11. At every loading, the OD method showed the least displacement and the TO method showed the greatest displacement of the incisors. The displacements in X, Y, and Z directions on 70-N loading are represented in Figure 12. The areas showing the highest deflection are indicated in red and those showing the least deflection are indicated in blue. Regional distributions of von Mieses stresses in the right screw-plating

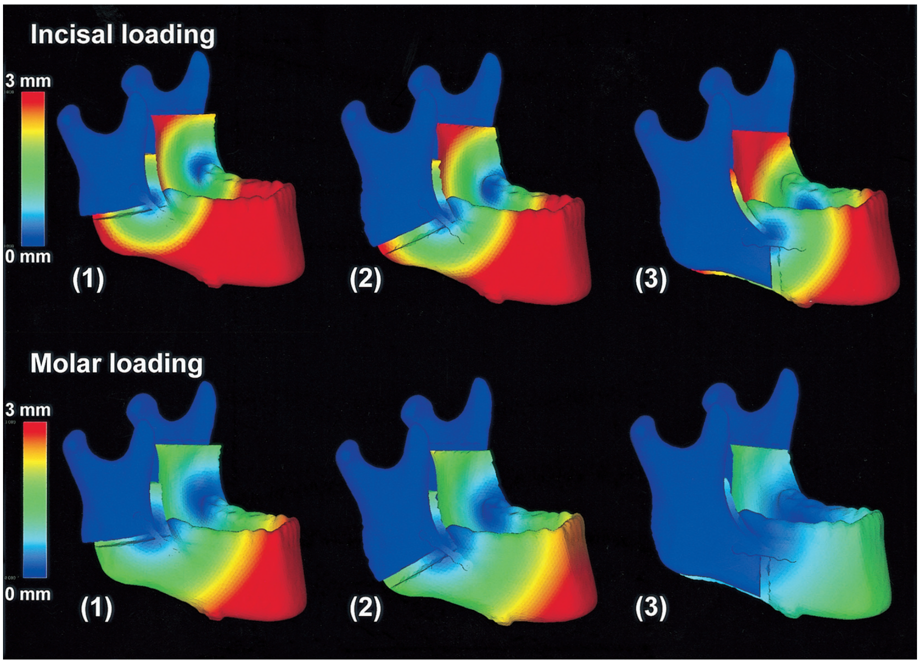

Figure 12　Mandibular displacements under simulated masticatory loads：⑴ Trauner–Obwegeser（TO）method, ⑵ Obwegeser original（Ob）method, and ⑶ Obwegeser–Dal Pont（OD）method

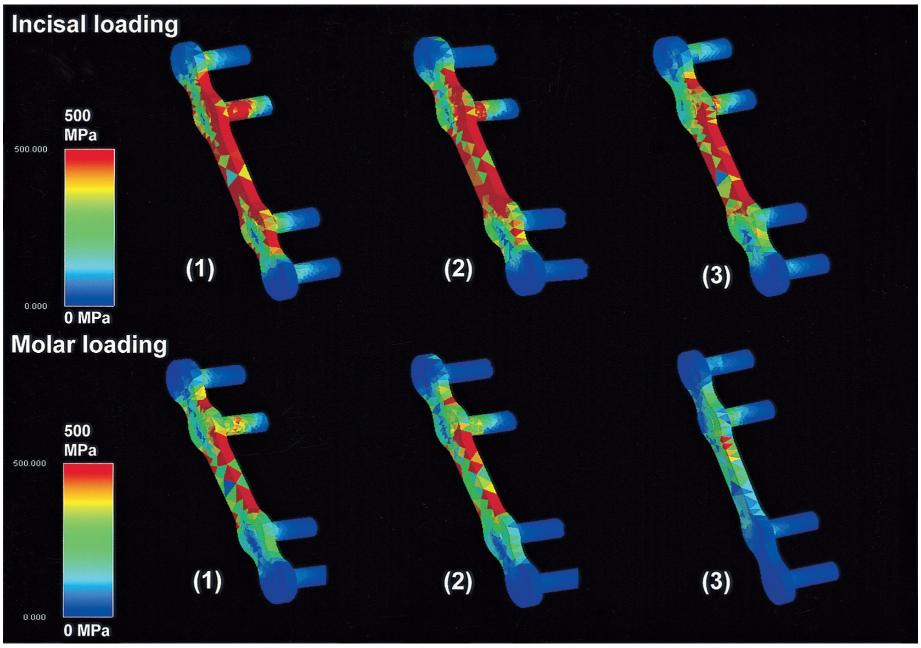

Figure 13　Regional distributions of von Mieses stresses in the right screw–plating system on 70–N incisal and molar loading：⑴ Trauner–Obwegeser（TO）method, ⑵ Obwegeser original（Ob）method, and ⑶ Obwegeser–Dal Pont（OD）method

Table 3 Comparison of central incisor and right first molar displacements with the maximum von Mieses stress values in the right screw–plating system on 70–N incisal and molar loading

	Incisal loading		Molar loading	
	Central incisor displacements (mm)	Maximum von Mises stresses in the right screw–plating system (MPa)	Righe first molar displacements (mm)	Maximum von Mises stresses in the right screw–plating system (MPa)
A) The Trauner–Obwegeser method	5.57	1565.33	2.96	903.77
B) The Obwegeser original method	4.49	1516.25	2.27	864.09
C) The Obwegeser–Dal Pont method	3.43	1239.13	1.23	501.09

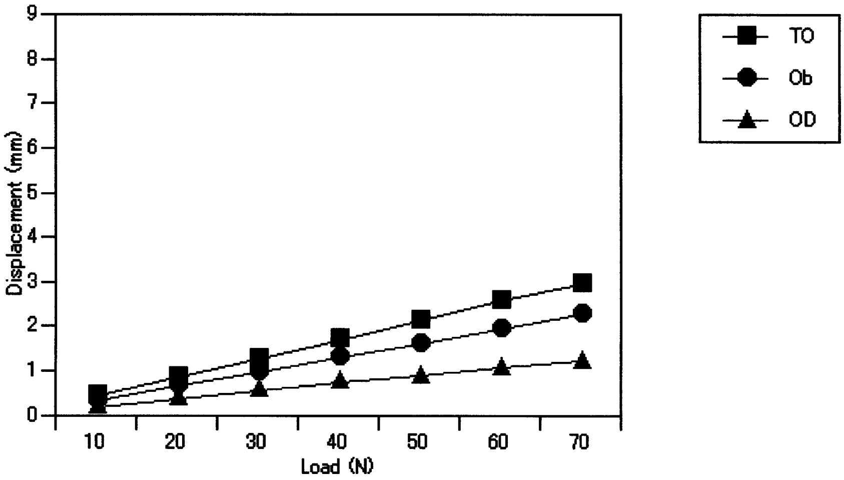

Figure 14 The load–displacement curves on molar loading in the finite element analysis (FEA) simulation

the right screw–plating system is given in Table 3. In this test as well, the OD method showed the least stress in the screw–plating system.

Discussion

Our study shows that the OD method allows greater mechanical stability of the mandible than the other two techniques. The results of the experimental study were in good agreement with those of the FEA simulation.

In both the experimental study and FEA simulation, the magnitude of displacement in the TO method was greater than that in the Ob method and the displacement in the OD method was significantly lesser than that in the Ob method under every loading condition (Figures 9–11 and 14). This means that the OD method provided the greatest resistance to displacement induced by the simulated functional forces.

In the FEA simulation, we also examined the maximum von Mieses stresses in the right screw–plating system on 70–N loading (Table 3). The least stresses were observed in the OD method and the highest stresses were observed in the TO method under both incisal and molar loading, which means that the OD method provided greater stability than the other two techniques. The smaller size of the lever arm in the OD method probably plays an important role in yielding lesser stress and smaller displacement.

Using FEA simulation, Puricelli et al.[3] suggested that the Puricelli osteotomy technique presents better mechanical stability than the original OD method. The Puricelli osteotomy is performed at a further distal region than the osteotomy in the OD method, performed anteriorly near the mental foramen. They speculated that owing to the increased surface area of medullary bone contact, a decrease in the size of the lever arm was obtained ; we agree with this interpretation of the results. However, in our FEA simulation, we did not consider bone contact (i.e., all the models were assumed to have perfect slippage at the bone interfaces). This assumption was made because osseous healing starts and is not completed in the early postoperative period. As a matter of course, a larger surface of bone contact promotes faster healing and has decreased displacement due to muscle activity.

The experimental model proposed in this study is an inexpensive, discriminating, and reproducible method to compare mandibular stability, but it has certain limitations15) : ⑴ the fixation systems were tested using forces applied vertically whereas mixed vertical, lateral, and rotational forces may be encountered clinically as dictated by the anatomical environment ; ⑵ the *in situ* plates may be affected by the physiological environment (e.g., inflammation or infection); and ⑶ the plates were subjected to a single continuous load and not repeatedly loaded as in normal function.

In addition to these limitations, FEA simulation also has some inherent limitations.16)17) The values of the stresses provided by FEA are not necessarily identical to the actual ones. In this study, we made several assumptions and simplifications regarding the material properties and model generation. In FEA models, bone is frequently modeled as isotropic, but it is actually anisotropic. In this study, bone was modeled as homogeneous, isotropic, and linearly elastic. Another crucial limitation is that the miniplates were not bent, whereas clinically the plates are often adapted to fit the contour of the bone surface.

The present study also showed the feasibility of FEA simulation, brought about by realistic representation of the stress distribution in the fixation material. FEA is a numerical method for addressing biomechanical questions and is a powerful research tool that can provide precise insight into the complex mechanical behavior of the mandible affected by mechanical loading, which is difficult to assess by other means.7)18)19)

Conclusions

1. The Obwegeser–Dal Pont method results in greater mechanical stability of the mandible than the other two techniques.
2. FEA is a useful method for estimating mandibular stability.

Acknowledgments

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