Three-dimensional Finite Element Analysis of Bone Fixation in Bilateral Sagittal Split Ramus Osteotomy Using Individual Models

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Abstract

The purpose of this study was to investigate factors involved in stress on locking mini-plate/screws used in orthognathic surgery based on patient-specific 3-dimensional finite element analysis. Data were obtained from 10 patients undergoing mandibular advancement by bilateral sagittal split ramus osteotomy. All underwent osteosynthesis with 2.0-mm titanium locking mini-plate/screws. A 3-dimensional finite element model of the mandible was created for each patient and each model subjected to the same loading conditions, which produced different stress values on locking mini-plate/screws. When the contact area of the proximal and distal bone segments was narrower and bone mineral density (BMD) lower, the von Mises stress values on the plate/screws were higher (contact area, \( p < 0.01 \); BMD, \( p < 0.05 \)). The present results suggest that bone contact area and BMD should be considered as plate stress factors.

Key words: Individual modeling — Finite element analysis — Bilateral sagittal split ramus osteotomy — Locking plate system

Introduction

Various modifications have been proposed to the operative approach to bilateral sagittal split ramus osteotomy (BSSRO). The first stepped osteotomy of the mandibular ramus was performed by Schuchardt\(^1\). This was followed by enlargement of the stepped vertical sections by Trauner and Obwegeser\(^2\), which increased bone contact area, resulting in an improved surgical technique that employed an intraoral method and offered good stability. This operative method was further modified to a technique that featured separate external and internal osteotomy procedures by Dal Pont\(^3\), Hunsuck\(^4\), Epker\(^5\) and Wolford et al\(^6\). These modifications contributed to substantial advances in mandibular osteotomy

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and rigid osteosynthesis.

Similarly, the internal fixation method for orthognathic surgery has been modified to achieve more rigid fixation by using mini-plate/screw systems rather than wires. Recently, BSSRO has been further modified to include locking mini-plate/screw systems, as this provides similar fixation to that achieved with bicortical fixation systems. Many orthopedic studies have investigated the strength and stability of locking mini-plate/screw systems from a bioengineering perspective. Few studies, however, have investigated these factors in orthognathic surgery.

Obtaining stability after BSSRO for mandibular retrusion has been reported to present difficulties in Caucasians. Only a few studies have investigated this in Japanese patients, however. One important factor influencing relapse is the stability of osteosynthesis.

Moreover, to our knowledge, no studies have investigated the mechanisms of osteosynthesis from a bioengineering perspective or used 3-dimensional (3D) finite element analysis (FEA) to conduct a postoperative analysis.

The purpose of this study was to investigate the results of BSSRO for mandibular retrusion by patient-specific 3D FEA in 10 clinical cases. Factors causing stress to the locking mini-plate/screw system are discussed.

Materials and Methods

Data were obtained on a total of 10 patients undergoing orthognathic surgery at the Chiba Hospital of Tokyo Dental College. The conditions for selecting these 10 patients were as follows:

1) All had undergone mandibular advancement by BSSRO for skeletal class II malocclusion.

2) The same surgical method was used in all patients and the procedure performed by the same operator. The BSSRO was performed using a procedure in which the external osteotomy line was modified to be compatible with the standard shape of the mandible in the Japanese population by using Wolford’s technique. An internal osteotomy was performed in the upper part of mandibular foramen using the Epker and Wolford technique. An external osteotomy was performed from the external oblique ridge at the buccal surface groove of the second molar to the antegonial notch (Fig. 1).

3) Internal bone fixation was performed using a Universal System 2.0-mm Orthognathic Sagittal Plate® (Stryker, USA) on both sides (Fig. 2). In this system, the body of the plate is made of pure titanium and the screws of titanium alloy.

4) All patients were Japanese, and none had any congenital disease.

At this institution, X-rays and computed tomography (CT) images are obtained before open-mouth training at approximately 1 month after orthognathic surgery. This is done to aid in assessing the status of osteosynthesis and contact between the distal and proximal bone segments. Therefore, CT data obtained at 1 month after orthognathic surgery were used for the analysis in the present study.

Table 1 shows the results of this analysis in each case. The SNA and SNB values revealed skeletal class II malocclusion in all patients. The range of advancement (mm) indicates

![Fig. 1 Surgical procedure](image)

- a) External osteotomy: From buccal surface groove of second molar to antegonial notch
- b) Internal osteotomy: Epker and Wolford technique
- c) Antegonial notch
- d) Lingual nerve
- e) Inferior alveolar nerve
- f) Mandibular foramen
the distance of mandibular advancement achieved by BSSRO. In cases 1, 2, 3, 4, and 5 this was between 4 mm and 9 mm. No differences were observed between each side in terms of range of advancement in any case. In cases 6, 7, and 8 advancement ranged between 6 mm and 9 mm. A 1-mm difference was observed between the two sides. In cases 9 and 10, the range was between 4 mm and 9 mm. A difference of 3 mm was observed between the two sides. The mandible had rotated horizontally in these two cases. This indicated poor stability after BSSRO in these patients. Mini-plate breakage was observed in 2 of the 10 patients, with this occurring at 2–3 months postoperatively in cases 5 and 10 (Fig. 3). No
plate breakage was observed on the post-BSSRO CT images, however.

Informed consent was obtained for use of the CT data from the patient or their parents or guardians in the case of minors.

1. Parameters of X-ray CT scans

Multi-slice CT images were obtained using a Somatom Plus 4 Volume Zoom® (Siemens Erlangen, Germany). The parameters for obtaining the consecutive slice images were as follows: tube voltage, 120 kVp; tube current, 117 mA; slice thickness, 1.25 mm; and slice interval, 1.0 mm.

2. Construction of 3-dimensional voxel mesh model

All the CT images were outputted in DICOM format to the TRI/3D-BON Image Analysis System® (Ratoc System Engineering, Tokyo, Japan). Next, 3D voxel mesh models were constructed corresponding to bone mineral density (BMD) values. Computed tomography data obtained from a Quantitative Bone Mineral Phantom UCA® (Kyoto Kagaku, Kyoto, Japan) were used to analyze the relationship between the BMD and CT values. The CT images of the phantom were obtained using the same conditions as those used in the patients. The average CT values of each reference were defined as the corresponding BMD value to create a calibration curve on TRI/3D-BON®. The 3D mesh models produced in this manner were based on volume data in which all elements comprised voxels (Fig. 4).

3. 3D-FEA parameters

The TRI/3D-FEM Stress Analysis System® (Ratoc System Engineering) was used to perform 3D FEA on the 3D mesh models. First, a 3D voxel mesh model of the mandible was created from the CT data of the patient. Cortical bone, cancellous bone, teeth, mini-plates, and screws were then extracted from the 3D voxel mesh model of the mandible by the CT values and each material constant applied (Fig. 5, Table 2)⁶,⁹,¹⁰. The mini-plates were simulated as a rigid body, similar to a locking system. All these factors were defined as 3D voxel elements with 3 degrees of freedom in the X, Y, and Z directions in a coordinate axis system. Construction of cancellous bone reproduced the status of bone cutting, contact, and osteosynthesis. Carter’s formula² was used for the BMD values to be converted into Young’s modulus according to the calibration curve. Thus, the converted values were used as heterogeneous elements corresponding to each voxel element.

The restraint conditions were to set the X-axis in the horizontal direction, the Y-axis in the sagittal direction, and the Z-axis in the vertical direction. Temporal bone, including the mandibular fossa, was fully restrained in all 3 directions. The portion corresponding to the buffer substance between the temporal bone and mandibular condyle was represented by a structure with the Young’s modu-
lus of articular disk; it was interposed to reproduce suspension of the mandible. The mandible was not restrained in any direction (Fig. 6). The 3D FEA loading conditions adopted were very simple and based on those used in previous studies.

Occlusal force was loaded onto the bilateral mandibular first molars. Occlusal force was determined based on a report by Takashima et al. As a bite force, a load of 203.84 N was placed on the mandibular first molar at 1 month after BSSRO. The direction and strength of muscle activity were determined based on reports by Yanagi et al. and Kojima et al. The relationship between the muscle attachments and the Frankfort horizontal plane was set as follows: the temporal muscle at 105° in the upper posterior direction; the masseter muscle at 50° in the upper anterior direction; the lateral pterygoid muscle at 80° in the upper lateral direction; and the medial pterygoid muscle at 125° in the upper medial direction. The muscle strength ratio was also set on the basis of the weight ratio by each jaw-closing muscle. The muscle strength ratio in the case of 203.84 N of bite force was defined as follows: temporal muscle, 90.84 N; masseter muscle, 45.09 N; and medial pterygoid muscle, 12.03 N. The same loading conditions were applied in all individual models (Fig. 7).

The following items were measured using TRI/3D-BON:

- Contact area (mm²): the contact area between the proximal and distal bone segments (Fig. 8).
- BMD value (mg/cm³): the average BMD value of the contact area between the proximal and distal bone segments.
- Average stress value (MPa): average von Mises stress value on the mini-plate/screw.
- Maximum stress value (MPa): maximum von Mises stress value on the mini-plate/screw.

4. Statistical analysis

Pearson’s correlation coefficient and stepwise multiple regression analysis were used to analyze the relationships among the average and maximum stress values of the individual models, range of advancement, contact area, and BMD values. The statistical analysis was conducted using SPSS version 11.0 software (IBM, Tokyo, Japan).

Table 2 Structural components and component properties

| Young’s modulus | Poisson’s ratio |
|-----------------|-----------------|
| Buffer substance | 44.1 | 0.4 |
| Cortical bone    | 14,000 | 0.3 |
| Cancellous bone  | According to BMD | 0.3 |
| Teeth            | 70,000 | 0.3 |
| Titanium plate   | 106,500 | 0.34 |
| Titanium screw   | 113,200 | 0.34 |

Results

Figure 9 shows the stress distribution map for each case. Each map has 255 color gradations. Red indicates high stress, while blue indicates low stress. Little stress was observed in the bone around the plate and high stress in the mini-plate in all cases. This stress was observed along the upper edge of the mini-plate, especially on the side of the proximal bone. In cases 5 and 10, broken lines were observed in this area and the mini-plate was subsequently found to be broken (Fig. 3).

Table 3 shows range of advancement, contact area, BMD value, average stress value, and maximum stress value in each model. While the same range of advancement was observed bilaterally in cases 1, 2, 3, 4, and 5, a difference was noted in contact area and BMD.

A 1-mm difference was observed in range of advancement between the right and left sides in cases 6, 7, and 8. Plate stress showed a correlation with contact area and BMD value. A large difference was observed in plate stress and contact area between the left and right sides in case 7. Case 8 showed the highest level of plate stress.

A 3-mm difference in range of advancement was observed between the two sides in
cases 9 and 10. In case 9, the difference in contact area was large, so the difference in plate stress was large. In case 10, although there was a difference in range of advancement, there was not much difference in contact area or BMD, and little difference in plate stress between the left and right sides.

Table 4 shows associations observed among range of advancement, average BMD values, and average and maximum stress values.
obtained using Pearson’s correlation coefficient. Range of advancement showed no correlation with contact area, BMD value, average stress value, or maximum stress value. A highly negative correlation ($r = -0.706$, $p < 0.01$) was found between average stress values and contact area. A negative correlation ($r = -0.571$, $p < 0.05$) was also found between maximum stress values and contact area. In addition, a negative correlation ($r = -0.531$, $p < 0.05$) was found between the maximum stress values and BMD values.

Table 5 shows the results of the stepwise multiple regression analysis conducted to comprehensively evaluate the above associations. The average and maximum stress values were dependent variables, whereas range of advancement, contact area, and average BMD

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**Fig. 8** Contact area

Contact area: contact area between proximal and distal bone segments. Contact area (yellow area) measured by TRI/3D-BON image analysis system® (Ratoc System Engineering, Tokyo, Japan).

**Fig. 9** Stress distribution maps for each case comprise 255 color gradations
Blue represents low stress and red represents high stress. Circumference area of plate and bone are shown.
### Table 3  Results for each case

| Case No. | Advancement range (mm) | Contact area (mm²) | BMD value (mg/cm³) | Average von Mises stress (MPa) | Maximum von Mises stress (MPa) |
|----------|------------------------|--------------------|--------------------|-------------------------------|-------------------------------|
| 1        | Right side 4           | 4,597              | 107.61             | 12.12                         | 56.51                         |
|          | Left side 4            | 4,037              | 108.44             | 12.37                         | 67.21                         |
| 2        | Right side 5           | 4,114              | 117.71             | 13.42                         | 69.48                         |
|          | Left side 5            | 3,098              | 111.74             | 12.35                         | 53.06                         |
| 3        | Right side 6           | 4,570              | 107.93             | 15.52                         | 86.67                         |
|          | Left side 6            | 4,795              | 108.00             | 10.67                         | 60.21                         |
| 4        | Right side 9           | 4,325              | 115.82             | 9.8                           | 57.92                         |
|          | Left side 9            | 4,573              | 115.28             | 12.6                          | 66.83                         |
| 5        | Right side 6           | 2,370              | 104.05             | 25.87                         | 154.89                        |
|          | Left side 6            | 2,808              | 109.88             | 23.82                         | 138.26                        |
| 6        | Right side 6           | 8,480              | 108.07             | 9.42                          | 66.19                         |
|          | Left side 7            | 8,320              | 110.40             | 8.44                          | 53.84                         |
| 7        | Right side 7           | 4,212              | 104.27             | 14.51                         | 75.31                         |
|          | Left side 6            | 6,440              | 109.73             | 6.86                          | 33.41                         |
| 8        | Right side 9           | 3,876              | 109.15             | 22.23                         | 140.79                        |
|          | Left side 8            | 5,032              | 109.05             | 19.59                         | 127.38                        |
| 9        | Right side 7           | 3,780              | 110.23             | 16.89                         | 113.61                        |
|          | Left side 4            | 5,175              | 112.72             | 13.36                         | 68.31                         |
| 10       | Right side 6           | 3,876              | 98.99              | 19.12                         | 134.25                        |
|          | Left side 9            | 3,980              | 97.27              | 20.20                         | 140.19                        |

### Table 4  Pearson's product-moment correlation coefficient

|                        | Advancement range | Contact area | BMD value |
|------------------------|-------------------|--------------|-----------|
| Advancement range      |                   |              |           |
| Contact area           | −0.026            |              |           |
| BMD value              | −0.067            | 0.156        |           |
| Average stress value   | −0.222            | −0.706**     | −0.436    |
| Maximum stress value   | −0.345            | −0.571*      | −0.531*   |

**p<0.01  *p<0.05

### Table 5  Multiple regression analysis

**Dependent variables: Average stress value**

| Independent variables | Multiple regression coefficient | Determination coefficient |
|-----------------------|---------------------------------|---------------------------|
| Contact area          | −2.283E-03**                   | 0.607                     |
| BMD value             | −3.544E-02*                    |                           |

**Dependent variables: Maximum stress value**

| Independent variables | Multiple regression coefficient | Determination coefficient |
|-----------------------|---------------------------------|---------------------------|
| Contact area          | −1.242E-02**                   | 0.526                     |
| BMD value             | −0.341*                        |                           |

*<p<0.05  **p<0.01
values were independent variables. The extent of the contact area showed significant association with decrease in average or maximum stress value. Furthermore, higher BMD values showed a significant association with a decrease in the average or maximum stress value.

Discussion

Many oral and maxillofacial surgeons have performed BSSRO as an operative method that offers good postoperative stability. However, few reports have provided mandibular advancement data regarding BSSRO in Japanese patients. In terms of the postoperative stability of mandibular retrusion, many studies have employed cephalometry to investigate the association between the range of advancement of the mandible and the method of osteosynthesis used. In terms of the state of postoperative osteosynthesis, however, biomechanical investigations of occlusion and chewing cannot be accomplished with individual patient data. Many FEA studies using the standard model have performed stress analyses of various states of osteosynthesis.

Keyak et al.\textsuperscript{11} presented an automated method for generating individual 3D FEA models of the human proximal femur. Their study used CT data to derive bone geometry and to estimate its inhomogeneous material properties. Similarly, they used TRI/3D-BON FEM software, which we also used in the present study, to obtain CT volume data and directly generate a 3D voxel model. This software can reconstruct both bone structure and states of osteosynthesis after BSSRO.

Previous studies attempted to establish a relationship between plate/screw placement configuration, plate/screw type, and BSSRO stability. Meanwhile, the present study used mechanical behavior under differing morphologies and the state of osteosynthesis in individual 3D FEA models. This allowed us to determine the effect of the locking mini-plate/screw systems in each model. However, 3D FEA has some inherent limitations. The stress values provided by FEA with the standard model are not necessarily identical to actual stresses. Takahashi et al.\textsuperscript{20} states that a crucial limitation of the standard model is that the mini-plates are not bent, whereas plates are actually bent to adapt to the bone surface in clinical practice.

In the present study, the individual 3D FEA models were made based on postoperative CT data. Thus, these individual 3D FEA models were more similar to the actual clinical status than would have been achieved with the standard model. The state of osteotomy splitting, osteosynthesis in the contact area, and plate adaption state were modelled on actual conditions after BSSRO.

Puricelli et al.\textsuperscript{15} measured stress according to different osteotomy methods using voxel-based meshes generated by CT with polyurethane mandibular models. Their study considered only 3 types: control (no osteotomy); Puricelli osteotomy; and the Obwegeser-Dal Pont method. They stated that the increased bone contact area of the proximal segment and consequent decrease in plate size applied to the mandible in the modified technique yielded lower stress values and displacements, and consequently offered greater stability after BSSRO. Takahashi et al.\textsuperscript{20} stated that the Obwegeser-Dal Pont method allows greater mechanical stability for the mandible than that of Trauner-Obwegeser or Obwegeser, and that mini-plates placed along Champy’s line provide a greater mechanical advantage than those placed at other locations. In both studies, when the bone contact area of the proximal and distal segments was wider, the mechanical stress was found to be lower. The same result was also obtained in the present study.

The biomechanical properties of locking and conventional titanium systems were evaluated by Gutwald et al.\textsuperscript{7} and Ellis et al.\textsuperscript{4}. Both were clinical reports and presented positive results, but were conducted on mandibular fracture patterns. To date, few studies have evaluated the fixation reliability of locking mini-plate systems after BSSRO.
Oguz et al.\(^{14}\) found that locking mini-plate/screw systems spread the load over the plate and screws and diminish the amount of force transferred to each unit. They reported that the von Mises stress at the locking mini-plate/screws was 77.07 MPa. In their study, 200 N bite force was applied to the models. However, additional studies are necessary to verify the clinical significance of their theoretical results. Throckmorton et al.\(^{22}\) reported that simulated bite force after BSSRO was 66.7 N on the central incisors and 260.8 N on the right first molar, which corresponded to the mean immediate postoperative bite force. Takashima et al.\(^{21}\) reported postoperative changes after BSSRO with an occlusal graph depicting bite force. In their study, postoperative bite force was 203.84±111.81 N. The direction of bite force in the present study was adapted from the same Japanese report. According to the report of Kojima, the weight ratio for each muscle was as follows: temporal muscle, 34.3 g; masseter muscle, 18.0 g; and medial pterygoid muscle, 5.2 g; with an assumed masseter criteria of 2:1:1/3\(^{12}\). In the present study, the muscle power ratio was set in the same way. Analyzing the direction of action of each muscle is very complex. Here, a very simple method was used as described earlier by Yanagi et al.\(^{25}\). At the initial stage of jaw movement at 1 month after BSSRO, it is still not possible for cutting to be performed with the anterior dentition. Therefore, occlusal force was set on the first molar only to reflect actual conditions following such a procedure. Furthermore, an articular disk-like structure similar to that found in the living body was simulated so that stress would be centered on the restricted side, as it would be under actual conditions. The von Mises stresses at the plate/screws were 33.41–154.84 MPa. These results show that stress values are determined by the shape and state of the model. The von Mises stress values in the cortical layer of the distal segment using the locking plate system were higher than those in other locations. And the stress on the locking mini-plate/screws (hereafter referred to as plate stress) affected the contact area between the proximal and distal bone segments. Stress increased as the contact area narrowed. The state of osteosynthesis and contact area were also investigated. Plate stress was indicated as the BMD value between the proximal and distal bone segments. Bone strength was determined by the BMD and bony structure, as approximately 70% of bone strength depends on the BMD\(^{15}\). The results revealed that the BMD value decreased as stress increased.

The tendency of plates to undergo stress was statistically analyzed by selecting reproducible factors and searching for correlations among them. The BMD measurements were also considered. Quantitative CT (QCT) procedures have been developed to determine BMD in the assessment of osteoporosis. This involves averaging the BMD values to determine its status. In the field of orthopedics, QCT has been used extensively to evaluate bone density, and geometry and has been described in distraction osteogenesis. Swennen et al.\(^{19}\) developed and validated a new method to objectively assess distraction regeneration using 3D QCT. They showed that 3D QCT-based bone densitometry was valid for research into distraction osteogenesis.

In the present study, both extent of contact area and high BMD values showed a significant association with decrease in the average and maximum stress values. This suggests that measurement of BMD based on 3D CT can provide a good indication of the state of osteosynostosis, and that this could therefore serve as a valid parameter in research into the start-time for mouth opening together with 3D FEA of plate/screw fixation. In two of the present cases, plate breakage occurred at 2 months after BSSRO, and these cases showed the highest stress values. These results suggest that, taken together, 3D FEA and BMD may offer a useful tool in predicting this type of plate breakage during mandibular advancement surgery by BSSRO.

Finite element analysis was performed using individual 3D FEA models. Usually, finite element analysis is used to simulate a fictitious model. However, the present study
demonstrates how this technique may be used in conjunction with clinical data to provide individual 3D FEA models. Furthermore, this technique is often applied to surface data arising from a homogeneous material. However, in the present study, this technique was applied using volume data arising from heterogeneous material. Our goal was to reproduce cancellous bone as a different material depending on BMD. Materials such as cortical bone, teeth, and plates usually appear as homogeneous materials in areas where CT values are unknown. Here, however, the focus was on the state of the junction at the mandible, so our goal was to reproduce a state as close to that which would be encountered in a clinical setting as much as possible.

Plate stress depends on muscular strength and occlusal force; it also depends heavily on other parafunctional elements. The purpose of this study was to investigate the influence of factors other than muscular strength and occlusal force on plate stress. Therefore, the same loading conditions were adopted for all models, that is, those prevailing at 1 month after BSSRO. The loading conditions were very simple, and an existing research method was adopted. The results of the FEM analysis of each individual 3D FEA model under the same conditions revealed that bone contact area and BMD were plate stress factors. In the two cases where the plate broke, the contact area was small and BMD value low, suggesting these as factors in the plate failure. In case 8, the plate did not break, although plate stress was very high. It is possible that a stable occlusal force was obtained in this patient and that the failure of the plate to break was down to sheer luck. Plate stress was treated as a transient load in this study. Postoperative plate stress usually occurs repeatedly, however, suggesting that further study needs to take metal fatigue of the mini-plate/screws into consideration also. It is speculated that this is also the reason for the disparity in the present results.

Further research is needed, however, to confirm the validity of the present results. Such work will possibly need to consider factors other than those already addressed here if it is to have clinical significance. We believe that not only prediction of plate breakage, but also postoperative stability in patients with jaw deformity can be secured.

We also believe that it may be possible to predict relapse using this method. If so, postoperative intermaxillary fixation may not be necessary, and this would improve quality of life for the patient.

References

1) Ammann P, Rizzoli R (2003) Bone strength and its determinants. Osteoporos Int 14: 13–18.
2) Carter DR, Hayes WC (1977) The compressive behavior of bone as a two-phase porous structure. J Bone Joint Surg Am 59:954–962.
3) Dal Pont G (1961) Retromolar osteotomy for the correction of prognathism. J Oral Surg Anesth Hosp Dent Serv 19:42–47.
4) Ellis E 3rd, Graham J (2002) Use of a 2.0-mm locking plate/screw system for mandibular fracture surgery. J Oral Maxillofac Surg 60: 642–645.
5) Epker BN (1977) Modification in the sagittal osteotomy of the mandible. J Oral Surg 35: 157–159.
6) Gedrange T, Bourauel C, Kobel C, Harzer W (2003) Three-dimensional analysis of endosseous palatal implants and bones after vertical, horizontal, and diagonal force application. Eur J Orthod 25:109–115.
7) Gutwald R, Alpert B, Schmelzeisen R (2003) Principle and stability of locking plates. Keio J Med 52:21–24.
8) Hunsuck EE (1968) A modified intraoral sagittal splitting technique for correction of mandibular prognathism. J Oral Surg 26:250–254.
9) Ichimura K, Yamaguchi H (2006) Bio-mechanical evaluation of mandibular widening distraction by three-dimensional finite element analysis. Shikwa Gakuho 106:215–227.
10) Katada H, Isshiki Y (2005) Changes in orthodontic cephalometric reference points on application of orthopedic force to jaw: three-dimensional finite element analysis. Bull Tokyo Dent Coll 46:59–65.
11) Keyak JH, Meagher JM, Skinner HB, Mote CD Jr. (1990) Automated three-dimensional finite element modelling of bone: a new method. J Biomed Eng 12:389–397.
12) Kojima T, Sato T (1992) A morphological study of the tendon in human masticatory muscle. Shigaku 80:342–366.
13) Oguz Y, Saglam H, Dolanmaz D, Uckan S (2010) Comparison of stability of 2.0 mm standard and 2.0 mm locking miniplate/screws for the fixation of sagittal split ramus osteotomy on sheep mandibles. Br J Oral Maxillofac Surg 10:1–3.
14) Oguz Y, Uckan S, Ozden AU, Uckan E, Esener A (2009) Stability of locking and conventional 2.0-mm miniplate/screw systems after sagittal split ramus osteotomy: finite element analysis. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 108:174–177.
15) Puricelli E, Fonseca JSO, Sant’Anna H, de Paris MF (2007) Applied mechanics of the Puricelli osteotomy: a linear elastic analysis with the finite element method. Head Face Med 3:38–44.
16) Schuchardt K (1955) Formen des offenen Bisses und ihre operativen Behandlungsmöglichkeiten. Fortschr Kiefer Gesichtschir 1:222–226.
17) Seide K, Triebe J, Faschingbauer M, Schulz AP, Püschel K, Mehrten SG, Jürgens CH (2007) Locked vs. unlocked plate osteosynthesis of the proximal humerus—A biomechanical study. Clin Biomech (Bristol, Avon) 22:176–182.
18) Shiki S, Takaki T, Noma H (2005) Stability after sagittal splitting ramus osteotomy in retrognathic patients. Jpn J Jaw Deform 15:59–67. (in Japanese)
19) Swennen GRJ, Eulzer C, Schuttyser F, Hüttemann C, Schliephake H (2005) Assessment of the distraction regenerate using three-dimensional quantitative computer tomogra-
phy. Int J Oral Maxillofac Surg 34:64–73.
20) Takahashi H, Moriyama S, Furuta H, Matsunaga H, Sakamoto Y, Kikuta T (2010) Three lateral osteotomy designs for bilateral sagittal split osteotomy: biomechanical evaluation with three-dimensional finite element analysis. Head Face Med 6:4–13.
21) Takahama H, Ihara K, Noguchi N, Goto M, Katsuki T (1999) Changes of masticatory function after sagittal splitting ramus osteotomy. From just before operation to one year after. Jpn J Jaw Deform 9:157–166. (in Japanese)
22) Throckmorton GS, Buschang PH, Ellis F 3rd (1996) Improvement of maximum occlusal forces after orthognathic surgery. J Oral Maxillofac Surg 54:1080–1086.
23) Trauner R, Obwegeser H (1955) Zur Operationstechnik bei der Porgenie und anderen Unterkieferanomalien. Dtsch Zahn Mund Kieferheilk 23:1–26. (in German)
24) Wolford LM, Bennett MA, Rafferty CG (1987) Modification of the mandibular ramus sagittal split osteotomy. Oral Surg Oral Med Oral Pathol 64:146–155.
25) Yanagi T, Tsuji Y, Kishi M (2001) The influence of location of occluding point and jaw elevator muscles forces on load of mandibular head. Shikwa Gakuho 101:649–666. (in Japanese)

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