ORIGINAL ARTICLE

A comparative study of most suitable miniplate fixation for mandibular symphysis fracture using a finite element model

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Abstract. The purpose of this study is to determine the most stable fixation method for mandibular symphysis fractures by comparing the mechanical characteristics of models fixed at different positions with different numbers of plates. Fractures were generated in 3-dimensional finite element models, and were fixed with a single miniplate, parallel double miniplates, or perpendicular double miniplates. A 300 N perpendicular load was then applied on the left molar region, and a finite element analysis was performed. We compared vertical gaps between the fractured surfaces, maximum stress within the screw/plating system, and maximum stress around screw holes in the bone. Compared to the single miniplate, both the parallel and perpendicular double miniplates demonstrated significantly less stress in the screw/plating system and screw holes in the bone. In addition, the perpendicular double miniplates had significantly smaller vertical gaps between fracture surfaces when compared to the single miniplate. Comparing parallel and perpendicular double miniplate fixations, less stress was found around the screw holes of the perpendicular miniplate models than those of the parallel miniplate models. There were no differences in vertical gaps or maximum stress within the screw/plating systems between the 2 double miniplate fixations. These results suggest that perpendicular double miniplate fixation is more suitable for fixing mandibular symphysis fractures. (Keio J Med 55 (1): 1–8, March 2006)

Key words: finite element analysis, mandibular symphysis fracture, miniplate, mechanical stress

Introduction

The mandible is the most frequent site among facial fractures.[1,2] Fractures with displacements are often treated by open reduction and internal fixation using miniplates.[1,3,4] When planning a surgical strategy for mandibular fractures, it is most important to obtain a rigid initial fixation to bear the masticatory load.

Mechanical analyses using a finite element analysis (FEA) have demonstrated that stability at the fracture interface differs with different plating strategies in both angle fracture models[5,6] and condyle fracture models.[7] Along with these fractures, the symphysis is one of the most frequent facture sites,[8–12] making up 18–20% of mandibular fractures in adults.[2,9] Children experience a higher proportion of symphysis fractures (14.5–40%) due to a more fragile symphysis caused by overcrowding of unerupted teeth.[10,11]

While stabilization is as important for symphysis fractures as other mandibular fractures, there has been relatively little study on an optimal method of internal fixation. This may be because, as the shape of the symphysis region is simpler than that of the angles or condyles, surgeons could assume that differences in fixation methods were less important. Little data exist on the selection of the number and positions of a plate, and these decisions are typically made empirically. To address this uncertainty, we used 3-dimensional FEA to investigate whether or not the stability of the fracture surface differs with different plating strategies.

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Material and Methods

CT scans and design of 3-dimensional mandible models

Computer models of adult human edentulous mandibles were created from CT scans of 8 dry human mandibles possessed by Department of Plastic and Reconstructive Surgery, School of Medicine, Keio University, as previously described by Nagasao, *et al.*[13]

Every fifth coronal plane slice (1 mm each in thickness) was picked, and the outer edge of the cortical bone and the boundary between the cortical bone and the cancellous bone were traced. Twenty to 30 points on the traced line were plotted on XYZ coordinates, and these points were then combined with straight lines to produce a wire frame. Then, adjacent wire frames were connected to each other. Therefore, 3-dimensional mandibular models composed of cortical bone and cancellous bone were created. The 8 mandibular models had different heights and widths. The coordinate data of mandibular models were imported to a personal computer (CF-Y2DW1AXR, Panasonic, JAPAN; CPU: 1.3 MHz Cash memory: 512 MB, HDD: 40 GB). And, all surgical simulations and analyses were performed using finite element analysis software (ANSYS Ver. 8.0, ANSYS Inc., Canonsburg, Pa., USA). Models were assigned with an orthogonal X-Y-Z coordinate system (Fig. 1): the X-axis was assigned as medio-lateral, the Y-axis cranio-caudal, and the Z-axis antero-posterior.

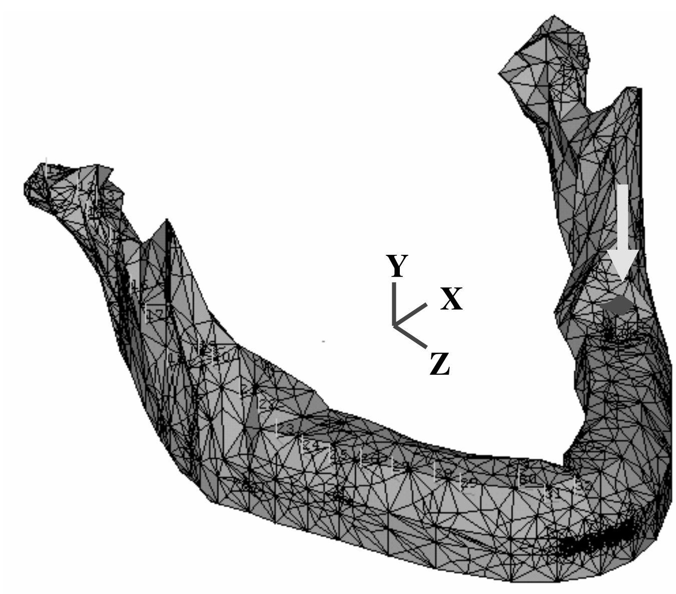

Fig. 1 3-dimensional finite element fractured mandibular model fixed with a single plate. A 300 N load was simulated perpendicular to the left molar region.

Generating fractures and fixing with different plating strategies

Next, we configured complete symphysis fractures that run on the midline in the sagittal plane, with fractured surfaces apposing each other.

Models of titanium fixation plates (4 holes, thickness 1 mm) were positioned in 3 different ways as described later on the buccal cortical bone surfaces, and fixed with unicortical cylindrical screws (diameter 2 mm). Although these screw models were designed without a groove, screws were united to the plates and buried in bone so that screw models were designed to be mechanically the same as actual screws.

These plates were curved along with mandibular contour and connected to the mandible only by screws. So, forces in the plates were transmitted to bones only by the screws.

The comparative conditions of miniplates were as follows (Fig. 2):

1. Single miniplate
2. Parallel double miniplates
3. Perpendicular double miniplates

The upper screws in both double miniplate models were positioned at the same location as those of the single miniplate model. The lower screws in the parallel miniplate models were positioned parallel to the upper ones at the inferior margin of the mandible. In other words, the long axis of all screws in the parallel miniplate model was parallel to the Z-axis.

In the perpendicular miniplate model, the lower screws were driven into the inferior surface of the mandible. The long axis of the lower screws was parallel to the Y-axis.

Screws were labeled #1: posterosuperior, #2: anterosuperior, #3: posteroinferior, and #4: anteroinferior (Fig. 2).

A 4 mm-diameter titanium dental implant was imbedded vertically into the left molar region. The head of the implant was given a cubic shape to simplify masticatory load calculations (Fig. 2).

Four models (intact mandible, symphysis fracture with single miniplate fixation, parallel double miniplate fixation, and perpendicular double miniplate fixation) from 8 individuals, a total 32 models, were created for the analyses. Each model was divided into 59,000–79,000 elements. Each element was tetrahedron-shaped, iso-parametric, and contained 10 nodes. All materials in this model were accounted for as isotropic, homogenous, and linearly elastic. We obtained the material properties for cortical bone, cancellous bone, and plating systems from previously reported data (Table 1).[13–15]

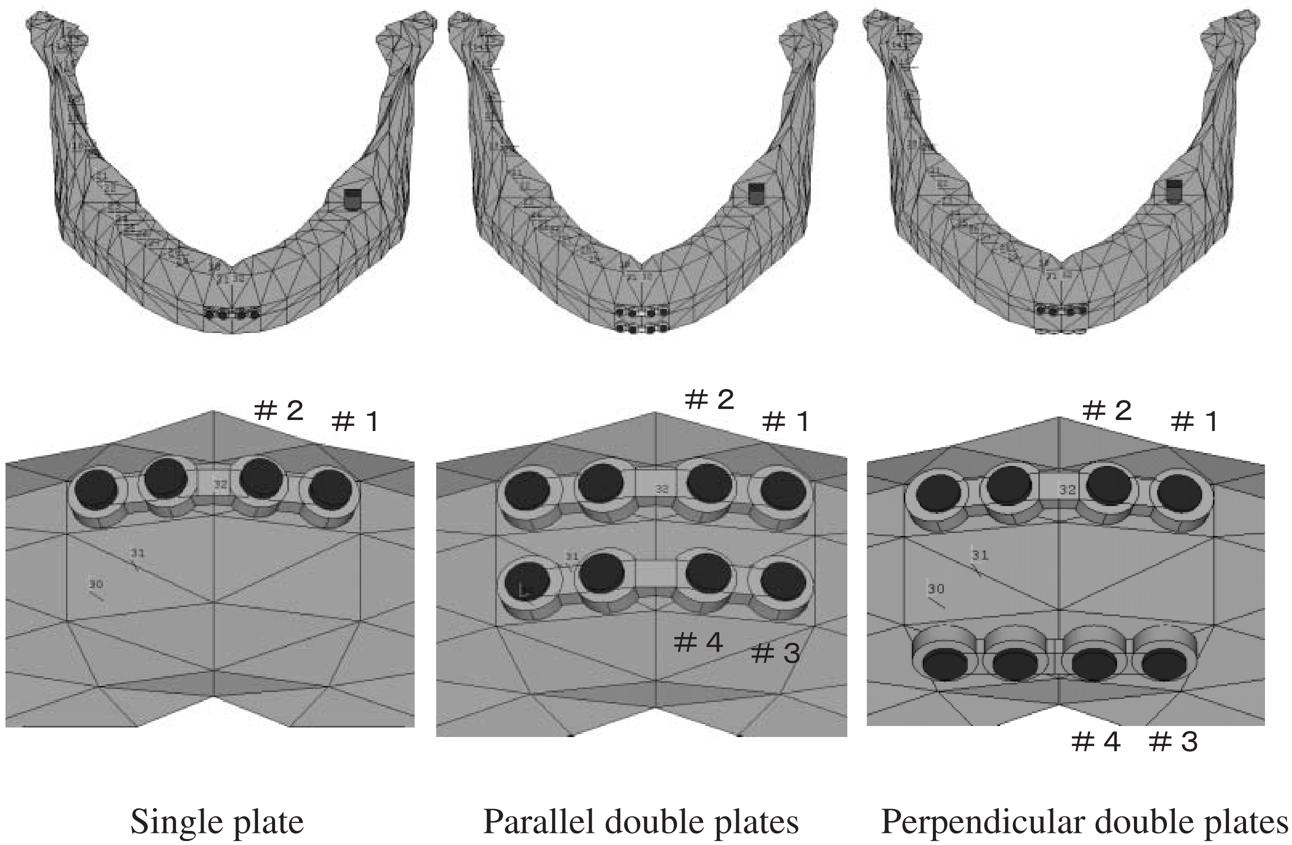

Fig. 2 Three types of plate fixation. Single miniplate: One curved miniplate was placed with four unicortical screws at the middle of the buccal cortical bone surface. Parallel double miniplates: Two parallel curved miniplates were placed with four unicortical screws, each on the inferior and the middle buccal cortical bone surfaces. Perpendicular double miniplates: One curved miniplate was placed on the middle buccal cortical bone surface and the other on the inferior surface, with four unicortical screws each. Screws were labeled as #1: posterosuperior site, #2: anterosuperior site, #3: posteroinferior site, and #4: anteroinferior site.

Table 1 Material Properties Used for the Calculations

	Elastic Modulus (MPa)	Poisson's Ratio
Cortical Bone	8700–15000	0.3–0.33
Cancellous Bone	500–1500	0.3
Titanium	105000–110000	0.34–0.35

MPa; Mega Pascal.

Constraints, loading, and solution

Six regions including condylar processes, coronoid processes, and mandibular angles, were fixed to zero displacement. A masticatory load on the left molar region was simulated with a 300 N force perpendicular to the dental implant (Fig. 1), which is the mean single molar bite force in healthy young adults.[16] It was assumed that the maximum masticatory load was applied to the molar region through the implant during mastication and clenching.

Evaluation and statistical analysis

The vertical gaps between the upper surfaces of the bilateral mandible fragments at the fracture site, the maximum stress within the screw/plating system, and the maximum stress around the bone screw holes were evaluated.

All stress values were recorded in MPa (Mega Pascals $= N/mm^2$). Data were compared for significant differences using the Mann-Whitney U test, with P-values < 0.05 being significant. All calculations were made using SPSS Ver. 10 for Windows (SPSS Inc., Chicago, USA).

Results

Stress distribution

The contour map of intact mandible models showed that von Mises stresses decreased gradually with distance from the loading region; little stress was found at

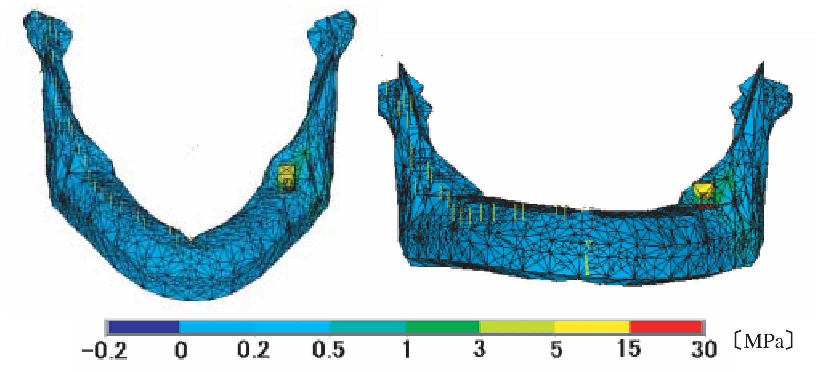

Fig. 3 Stress distributions in the intact mandibular model by a 300 N vertical load. Stress was mainly localized around the loading region. MPa; Mega Pascal.

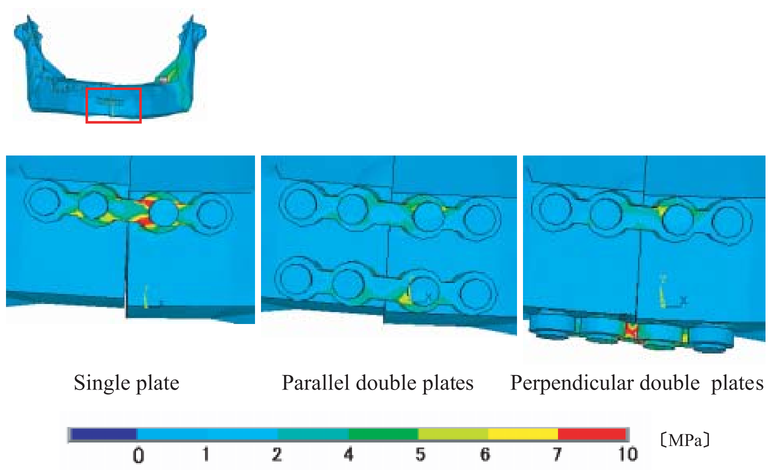

Fig. 4 Contour maps of the stresses within the screws by a 300 N vertical load. Different scales were used for fractured models because of the difference in the stress levels. Stresses were concentrated within the screws near the fracture site (#2 and #4) in all groups. Each model had a displacement of the borders of the fractured surface of varying degrees. MPa; Mega Pascal.

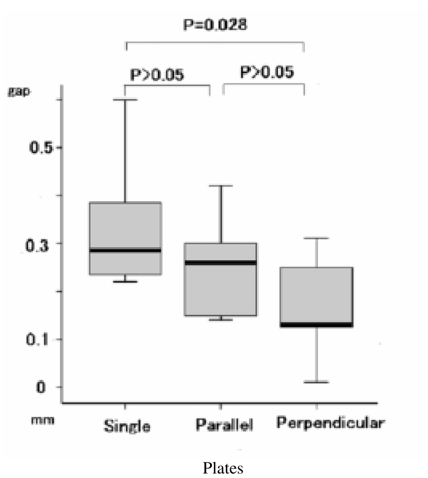

Fig. 5 Gaps between the upper borders of the fractured surfaces. There was no significant difference in the distance of the gaps between the perpendicular double miniplates models and the parallel double miniplates models, while there was significant difference between the perpendicular double miniplates models and the single miniplate model.

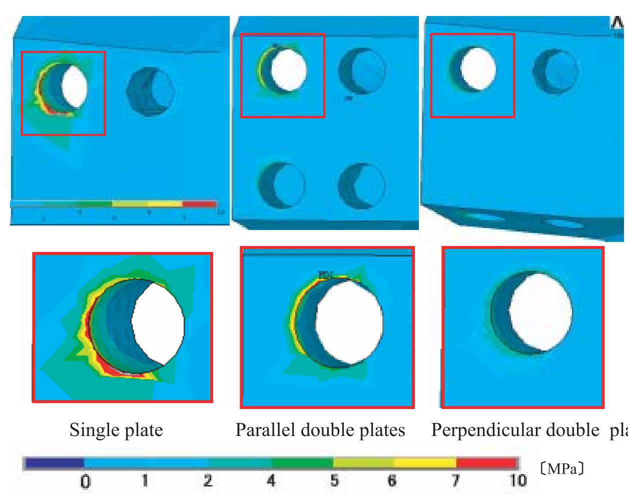

Fig. 6 Contour maps of the stress around #2 bone screw holes. The stress concentration was determined around the #2 bone screw hole in each group (*upper row*). Close-up (*lower row*) shows that perpendicular double miniplates had the least stress around the #2 bone screw hole among these three fixations. MPa; Mega Pascal.

Table 2 Maximum von Mises Stresses at #2 Screws and Screw Holes and Gaps between the Fractured Surface in the Different Plates Fixation

Fixation	Single plate		Double plates			
Positions of plates			Parallel		Perpendicular	
	Median	Range	Median	Range	Median	Range
Maximum stress at #2 screw (MPa)	15.50	8.7–16.4	10.32	4.6–17.0	7.97	6.2–12.5
Maximum stress at #2 screw hole (MPa)	13.91	7.0–21.4	6.6	3.8–8.8	2.61	1.2–4.4
Gap between the upper borders of the fractured surface (mm)	0.293	0.22–0.6	0.255	0.14–0.42	0.171	0.01–0.31

MPa; Mega Pascal.

the symphysis region (Fig. 3). In symphysis fracture models, von Mises stresses were concentrated within the #2 and #4 screws, regardless of fixation patterns (Fig. 4).

Gaps between the upper surfaces of the bilateral mandible fragments at the fracture site

Each fixation method had a gap at the upper border of the fractured surfaces (Z-axis, Table 2). The perpendicular miniplate models demonstrated significantly smaller gaps than the single miniplate models ($p = 0.028$, Fig. 5), but there was no significant difference in the gaps of the upper border of the fractured surface between the parallel and perpendicular miniplate models.

Maximum stress around screw/plating systems

Comparing the 3 fixation models, mechanical stress within screw/plating systems differed (Fig. 4). In the single models, the maximum stress was found within screw #2. In the parallel models, the stress within screw #2 was reduced and appeared to be dispersed to screw #4. In the perpendicular models, the maximum stress was found in the middle of the inferior plate.

Among these models, there were no statistically significant differences in stress within screw #2, although there was a trend for the stress to be lowest in the perpendicular models and highest in the single models (Table 2).

Maximum stress at bone screw holes

The lowest maximum stress around screw hole #2 was found in the perpendicular models, followed by the parallel models, and finally the single models (Fig. 6, Table 2); these differences were significant (Fig. 7).

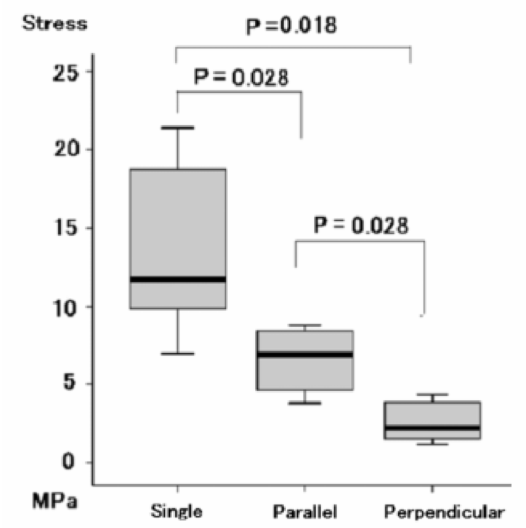

Fig. 7 Maximum stress around #2 bone screw holes. The perpendicular double miniplates had significantly lower stress, followed by the parallel double miniplates, and then the single miniplate.

Discussion

The purpose of surgical fixation for mandibular fractures is to secure the reduced fragments during osteogenesis to permit sound healing. Inevitable frequent masticatory loads can cause motion at the fracture site, and interfere with the healing process. As a result, nonunion can occur in symphysis fractures, the rate of which has been reported to be 3.7%.[12] Inadequate stabilization or reduction was an important cause of nonunions.[24] Therefore, we sought the most effective fixation method to stabilize a fracture, which results in less mechanical stress on the mandible, in this study.

The symphysis is one of the most frequent sites of mandibular fractures in children, and comprises about 20% of adult mandibular fractures.[9] Symphysis fractures with displacement are often fixed with 1 or 2 miniplates. Although there have been some reports on mechanically appropriate positions for miniplates in mandibular angle[5,6] and condyle fractures,[7] few such studies exist for symphysis fractures.

A possible reason for this paucity is that the anterior surface of the symphysis region is moderately convex and easily accessed, so it might be accepted as axiomatic where the miniplates should be placed.

However, the anterior surface of the symphysis region forms an angle with the inferior surface, presenting multiple options for positioning plates and screws. We hypothesized that in the symphysis fracture, the fracture stability will differ with the positions of plates and screws chosen. We tried to answer this question using 3-dimentional FEA.

In this study, we created 3-dimensional mandibular models to simulate the 3 fixation techniques. *In vivo* strain gauge measurements are alternatives to FEA,[17–19] but stress-measuring areas and the number of measuring devices are limited due to the volume of the gauge. FEA permits an analysis of stress from arbitrary points, and provides other useful information such as on distances, stress, and behavior of the whole model. There are many reports on FEA for angle fractures,[5] condylar fractures,[7] and other mandibular conditions.[5,7,13,15,20,21] We, therefore, determined that FEA was suitable for this application.

The masticatory load we simulated was a 300 N vertical load on the left molar region. While masticatory motion is actually like a teardrop cycle,[22] which means the frontal plane trace of a molar is like a teardrop not a straight line, the vector mostly consists of a vertical component (Y-axis, Fig. 1), so we considered a vertical load to be a reasonable approximation.

We evaluated 3 items for plate stability: 1. gaps between the upper border of the fractured surfaces, 2. maximum stress within the screw/plating systems, and 3. maximum stress around the bone screw holes. Stress within the screw/plating systems and bone screw holes can cause screw loosening and incomplete stability of the fractured surfaces, therefore, low stress is favorable for stability. The gap between the upper borders of the fracture surfaces is a direct indicator of stability. The upper borders of the fractured surface were appropriately evaluated by Y-axis motion, as they were hardly affected by X-axis motion (Figs. 1 and 4).

It was derived from animal experiments using the dog[23] that fracture displacement should not exceed 150 μm for proper healing. From our findings, the perpendicular miniplate models give the best result that is close to that of the dog experiment (Table 2, Fig. 4). Unless applying maximum bite force, sound healing would be expected with perpendicular fixation. *In vivo* strain measurements demonstrate that the maximum stress around screw holes peaks at 2 weeks postoperatively when maximum bite force is applied;[17] therefore, achieving stability of the fracture site is essential for 2 to 3 weeks.

The parallel miniplates models demonstrated significantly less stress than the single miniplate models in both the screw/plating system and bone screw holes, but no significant difference was found in the gap at the upper borders of the fractured surfaces.

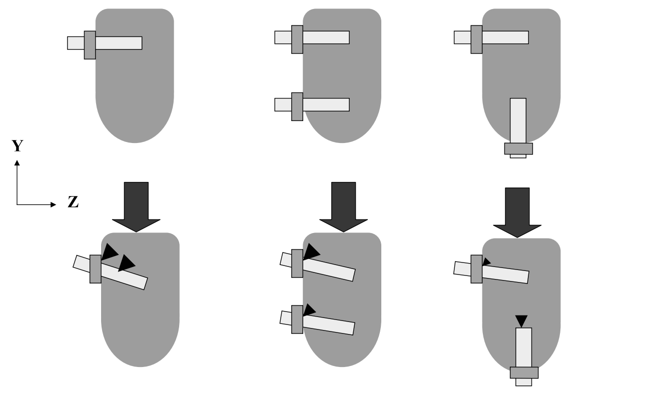

Fig. 8 Mechanism of stress transmission. These are the cross sections of mandibular symphysis regions (*upper row: resting state; lower row: loading state*). When a vertical load is applied (*arrows*), stresses were transmitted to screws (*arrowheads*). In the single miniplate model, the stress was concentrated at the screw end that is connected to the plate. In the parallel double miniplates model, stress was dispersed over the two screws. In the perpendicular double miniplates model, vertical stress was mainly transmitted to the inferior screws, whose long axis is in the same direction to the load. Ultimately the stresses on the screws were transmitted to the whole plate.

The perpendicular miniplate models also demonstrated less stress than the single miniplate models in both the screw/plating system and bone screw holes, while having significantly smaller gaps at the upper border of the fractured surfaces.

Less stress was demonstrated around the screw holes of the perpendicular miniplate models than those of the parallel miniplate models, but there were no differences in the gaps or the maximum stress within the screw/plating systems.

These data indicate that double miniplate fixation can lead to better stability regardless of plate position, however, more stress would occur around bone screw holes in parallel miniplates fixation. As illustrated in Fig. 8, this phenomenon can be explained by the relationship between the vector of masticatory load and the inferior screws (Fig. 8). Plating systems are mainly subject to a downward force along the Y-axis (Fig. 8, arrows). Miniplates resist shear forces along the Y-axis as well as bending that would lead to a gap along the X-axis. In the parallel models, shear forces were applied to the screws embedded perpendicular to the Y-axis (Fig. 8, center; Fig. 9 left, dot areas). While one end of the screw was connected to the miniplate, the other end was free (Fig. 9 left, circle). Applying a masticatory load, the stress was resisted only by the junction of the

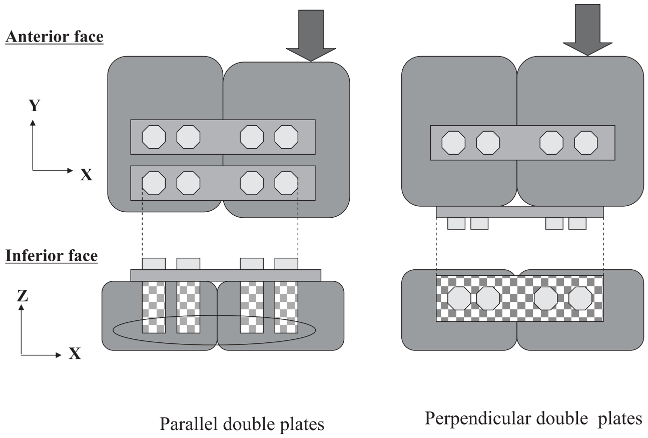

Fig. 9 Schema of mandible and screw/plating systems. Frontal views (*upper figures*) and axial views (*lower figures*) of the fractured mandible fragments. In parallel double miniplates models, stress was transmitted to the long axis of screws because they were embedded perpendicular to the loading vector (*lower left, dot areas*). One of the ends was imbedded directly in cancellous bone (*lower left, circle*). In the perpendicular double miniplates models, the screws only transmitted the stress because the long axis of the screws was parallel to the loading vector. The stress was resisted by the plate that was vertical to the masticatory vector (*lower right, dot areas*). Both ends of the plates were firmly stabilized with screws; therefore the plate could endure the stress securely.

screws and miniplate (Fig. 8 center, arrow heads).

In the perpendicular models however, the screws only transmitted the stress because their long axis was parallel to the force, and the stress was resisted by the plate instead of the screws vertical to the masticatory load (Fig. 9 right, dot areas). Because both ends of the plates were firmly stabilized with screws, the plates could endure the stress well (Fig. 9 right, dot areas).

Therefore, in the perpendicular models, less stress occurred around bone screw holes, despite no difference being found within the screw/plating systems between the perpendicular models and the parallel models. Additionally, plate fixed on the inferior surface directly secures X-axis motion, and can contribute to the stability of the entire fractured surface.

In conclusion, the perpendicular double miniplate fixation was found to provide better stability for the fractured surfaces and less stress at the bone screw holes, giving them favorable fixation for mandibular symphysis fractures.

Although, in the actual operation, perpendicular double miniplate fixation needs a wider exposure, we think that a complete reduction of the dislocated segments under a wider exposure leads to better stability, and contributes to sound osseous healing. Because neovascularization at fractured site, which is essential for osseous healing, occurs faster at the cancellous side of cortical bone, the blood supply for which is supplied by the inferior alveolar artery, than at the outer side supplied by mandibular periosteum.[25]

Regarding the skin incision, intraoral incision is usually employed for the exposure of mandibular symphysis fractures, and the inferior surface of the mandible can also be exposed from this incision excluding the need of another incision for perpendicular miniplate placement.

Even though we started our simulation study with titanium plates and a vertical load, we are planning to perform analyses using different materials and different loads such as anteroposterior shear load that would cause considerable fracture movement along the Z-axis.

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