Biomechanical analysis of the human mandible in surgical operations

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ABSTRACT

The ramus split osteotomy was examined from mechanical engineering view points. In order to simulate the mechanical effect caused by the surgical operation, three-dimensional finite element model of the human mandible was proposed. Using the model, we examined the mechanical response during biting after the surgical operation. The computational results showed that the model serves useful knowledge in surgical operations.

1 INTRODUCTION

The ramus split osteotomy is a useful technique for a patient who has mandibular skeletal deformity. The surgical technique is a process which splits the both sides of the patient’s mandible and fixes the bony segments with metallic screws or plates as shown in Fig. 1 [1]. It improves the masticatory function by adjusting the relative position to upper teeth. It is important to make a precise surgical planning to recover masticatory function after the recovery.

Recent technology supports us to make the surgical planning. Two types of techniques are mainly used for the planning. One is a way of using computer graphics. Volume rendering technique reconstructs three-dimensional image of mandible from CT digital data around a patient’s head [2]. Using the technique,
we can make a surgical simulation on a computer, splitting the mandibular image at various portions and moving the split bony segments for proper arrangement. The other one is a way of making an individual solid model with artificial material. A multi-axial milling machine produces the mandibular model from CT digital data [3]. Surgeons easily perceive the patient’s mandible by hand before the surgical operation. These two techniques are a sort of morphological simulation.

However, the ramus split osteotomy has still an important problem which must be given in consideration. That is mechanical response of the mandible after the surgical operation. The reason why we should discuss the problem is that mechanical properties around split portions must be greatly changed. The joining portions between bony segments are considerably weak for a while after the surgical operation. The mechanical response is expected to be quite different between pre- and post-operative conditions. There are few studies on this point. This paper aims to examine the mandibular mechanical events in surgical operations by executing a sort of biomechanical simulation.

![Figure 1: Diagrams of mandibular osteotomy. These figures were drawn by authors based on the reference[1]. (a) split of mandible, (b) metallic screw fixation, (c) metallic plate fixation.](image)

2 FINITE ELEMENT MODEL FOR SURGICAL SIMULATIONS

In order to analyze the mechanical behavior of bony segments after the surgical operation, we proposed a finite element mandibular model. Fig. 2 shows the model of the human mandible. The total elements and nodes are 2466 and 3618 respectively. The elasticity of Young's modulus of outer elements are set as 1.0x10 GPa. As the front portion of mandible is shell-structured, the elasticity of inner elements is selected as 1/100 compared with outer elements. The poisson's ratio is set as 0.3 for all elements.

The model consists of several flat blocks to represent the surgical operation as shown in Fig. 3. A joining portion is inserted between bony blocks. The mechanical property of the joining portion is an important factor because it greatly influences stress distribution and deformation of the body. The modulus of the joining portion gradually increases on the way of recovery. We can
simulate the recovery process by changing the modulus of the joining portion.

We studied the mechanical performance of screw fixation and plate fixation. In the former case, we can set various screw positions by giving Young's modulus of the screws. The fixation with screws is represented by giving the Young's modulus of the metal \((2.1 \times 10^2 \text{ GPa})\) to the corresponding elements. In the latter case, we added some elements representing a metallic plate to the mandibular model. Fig. 4 shows the plate type of elements. Actual mechanical situation is more complicated than this model. It must be checked whether stress patterns around metallic parts are reliable. To examine the validity of the whole model, we provided a specialized model for precisely simulating mechanical events around metallic parts. We will also discuss the problem later.

![Three-dimensional solid model](image)

**Figure 2:** Three-dimensional finite element model of the human mandible. Small black elements in the side view denote places fixed with screws.

![Figure 3](image)

**Figure 3:** Modeling of split bony segments. The joining portion is changeable by removing some parts. As described below, we left the only hatched part and examined the mechanical effect by the reduction.
3 STRESS ANALYSIS

To execute stress analysis, we must determine biting conditions of the model. For the first step of mechanical estimation, we set a typical unilateral biting as shown in Fig. 5. The masticatory forces and the directions are determined set as shown in Table 1 referring to other researchers' study [4]. Fig. 5 (right side) also shows the boundary condition around condyles. Both condyles can turn in any direction like a pivot and one side of condyle can also move freely along one direction. We adjusted moment balance around Y-axis producing the muscular forces and the biting force. These forces are distributed to several nodal points to avoid stress concentration.

First, we analyzed stress distributions under post-operative condition fixed with 3 screws or with metallic plates. The stress analyses were performed by the general purpose structural program, NISA II (EMRC Corp.). The joining portions between bony segments were set 1/100 of Young’s modulus of other elements assuming that the several weeks passed after the operation. Fig. 6 and 7 show the equivalent stress distributions by screw and plate fixations respectively. Stress concentration around screws is not recognized. On the other hand, plates are highly stressed compared with other portions. These results seem to be disadvantage for plate fixation. To examine the mechanical events around the plate fixation more precisely, we executed stress distributions under contact states using a partial model.

Contact analyses were executed using a structural program called ANSYS (Swanson Analysis System). The one of results is shown in Fig. 8. The stress pattern around a plate occurred in the partial model is similar to that in the total model. The plate's region is highly stressed, but the bony parts even in the near the plate are not stressed. The levels of the stresses are less than 1/10 of stress value at the plate. This result suggests us that plate fixation has not disadvantage to the mandible, rather shows preferable mechanical response.
Table 1: Masticatory forces and the directions.

<table>
<thead>
<tr>
<th></th>
<th>Masticatory forces</th>
<th>Directions (Balancing side)</th>
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<tr>
<td></td>
<td>Working side(kgf)</td>
<td>Balancing side(kgf)</td>
</tr>
<tr>
<td>Ta</td>
<td>5.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Tp</td>
<td>2.0</td>
<td>3.6</td>
</tr>
<tr>
<td>M</td>
<td>8.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Pm</td>
<td>3.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Pl</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>B</td>
<td>13.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5: Unilateral biting condition (Left) and boundary condition for stress analysis (Right).

Figure 6: Equivalent stress distribution (fixed with 3 screws for each side). Stresses around screws are not so high compared with other regions.
Figure 7: Stress distribution (fixed with a plate for each side). Plate type of elements are highly stressed compared with other regions.

Figure 8: Computational result. Two flat blocks are in contact and fixed with a metallic plate. (Left: equivalent stress distribution, Right: mechanical condition)

4. EXPLANATION OF SURGICAL EFFECT

Using the proposed model, we tried to simulate an actual surgical operation. Fig. 9 (left side) shows a side view of a mandibular image after the ramus split osteotomy. Two small circles in the image are screws' positions. Compared with our mandibular model, there are some differences. The number of screws is two, and the joining area between bony segments is considerably small.

The operation was not favorable progress. The right side of two figures show the frontal images in pre- and post- operations respectively. The bony segment was slightly tilted on the way of recovery. It is supposed that the connected portions in the mandible received excessive stresses. We tried to evaluate the degree of the stress using our model.

To simulate the instance, we computed the stress distribution in the mandible fixed with 2 screws. The joining area between bony segments was
reduced to the shaded area as shown in Fig. 3. The computational result is shown in Fig. 10. The maximum stress and displacement between condyles are shown in Table 2 including other cases. The maximum stress increases about 3 times compared with the case of 3 screws. Table 2 also tells us that if the joining areas are not reduced, the maximum stress does not rise even in case of the 2 screws' fixation. This means joining portions play an important role to support bony segments even if they are not rigid. It is effective for mandibular osteotomy to make joining area as large as possible.

Figure 9: Actual surgical operation. This instance shows unfavorable recovery because left bony segment was inclined after surgical operation. Two small circles denote positons of screws.

Figure 10: Stress distribution after reducing joining area (2 screws' fixation). Large stresses are set up around two screws on the balancing side.
Table 2: Comparison of surgical simulations.

<table>
<thead>
<tr>
<th></th>
<th>maximum equivalent stress ($\times 10^6$ MPa)</th>
<th>displacement between condyles ($\times 10^{-4}$ m)</th>
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<tbody>
<tr>
<td>normal</td>
<td>1.018</td>
<td>4.209</td>
</tr>
<tr>
<td>plate fixation</td>
<td>5.016</td>
<td>4.882</td>
</tr>
<tr>
<td>3 screws fixation</td>
<td>1.023</td>
<td>5.232</td>
</tr>
<tr>
<td>2 screws fixation</td>
<td>1.024</td>
<td>5.339</td>
</tr>
<tr>
<td>2 screws fixation*</td>
<td>3.184</td>
<td>7.154</td>
</tr>
</tbody>
</table>

The last row (*) shows a case that joining portions are reduced.

5 CONCLUSION

Mechanical behavior of bony segments in mandibular osteotomy was discussed from a standpoint of biomechanics. The computational results showed that the joining area of bony segments is an important factor to decrease the mechanical effect after the surgery. The proposed model is applicable to various problems, for example, optimum arrangement of screws or plates, estimation of mechanical effect by change of biting condition. The authors have developed an individual modeling method based on X-ray CT data [5]. Utilizing the method, individual biomechanical simulations will be realized and lead to successful surgical operations with high reliability.

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