Finite Element Analysis of Movement of Lower Jaw Molars Using Implant Anchor

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Abstract
The movement of the molars of a lower jaw subjected to distal loads from an implant anchor, a correcting wire and brackets was investigated using a three-dimensional finite element method. The finite element model consists of the lower jaw, teeth, periodontal membranes, the correcting wire and brackets. The lower jaw and teeth were constructed on the basis of computed tomography (CT) images of a dried human skull. The Young’s modulus of the lower jaw was obtained from the gray value data of the CT images. The implant anchor was not considered in the model. However, the position of the anchor was used to determine the direction of the force acting on the wire. The movement of the molars was compared with that of a lower jaw model obtained experimentally using a three-dimensional digital image correlation technique. Results indicated that the movement of the molars depended on the position and direction of the load.

Key words
Dental Correction, Implant Anchor, Lower Jaw Molars, Movement, Finite Element Analysis, Digital Image Correlation

1. Introduction
Dental correction is mainly conducted to correct abnormal occlusions such as an irregular bite [1]. Correcting wire techniques [1], implant techniques and mixed techniques [2], in which implants are used together with correcting wires, are mainly used for dental correction. In dental correction, teeth must be moved in the desired direction and by the desired amount. Therefore, the magnitude and direction of the force acting on teeth must be known before correction, which are currently determined from experience. Consequently, the mechanical study of dental correction is desirable.

Experimental techniques, such as photoelasticity [3-9], digital image correlation [10-12] and electronic speckle pattern interferometry (ESPI) [5],[13-16], and numerical techniques, such as finite element (FE) analysis [17-23], are used for mechanically studying dental correction. However, the application of experimental results to individual patients is difficult because standard models made of artificial materials such as epoxy resin, which differ from actual materials such as bone and tooth, are used. In finite element analysis, there are two major problems: the difficulty in the three-dimensional (3D) modeling of the complex shapes of bones, teeth and periodontal membranes and the difficulty in assigning mechanical properties to their materials. X-ray computed tomography (CT) images taken from a living body have recently been used to reduce the difficulty in modeling and assignment as follows [18-23].

Using a 3D homogeneous FE model constructed on the basis of CT data, the stress distribution in bone during the movement of the upper jaw first molar has been analyzed [18]. Furthermore, using such CT-based models, the dental/periodontal stress distribution caused by the movement of lingual and distal tipping teeth (lower canine and upper and lower molars) and the reaction of a single-rooted lower canine with a miniscrew used for skeletal anchorage under a load have been investigated [19],[20]. The stress-strain responses of a lower jaw to orthodontic tipping loading have been investigated using a CT-based 3D homogeneous FE model including orthodontic hardware such as brackets and correcting wires [21].

Using a CT-based 3D inhomogeneous FE model without orthodontic hardware, the stress distribution in bone during the movement of the upper and lower dentition has been analyzed [22]. Furthermore, the stress distribution in the root surroundings during upper anterior retraction has been investigated by a digital image correlation technique assisted by FE analysis using a CT-based 3D inhomogeneous model without orthodontic hardware [23]. For these inhomogeneous models, the Young’s modulus of bone has been obtained from the gray value data of CT images. However, the movement of lower molars subjected to orthodontic loading from implant anchors has not been investigated using a CT-based 3D inhomogeneous FE model with orthodontic hardware such as brackets and correcting wires.

In this study, we investigated the movement of the molars of a lower jaw subjected to distal loads from an implant anchor, a correcting wire and brackets using a 3D inhomogeneous FE model constructed on the basis of CT data. The movement of the molars was compared with that of a lower jaw model obtained experimentally using a 3D digital image correlation technique.

2. Finite Element Analysis

2.1 Analytical model
Radiographic CT images of a dried human skull taken with a 0.6 mm slice width by X-ray CT equipment were utilized to develop a 3D FE model (analytical model) of a lower jaw with teeth. The number of images used was 322. Solidification was conducted on the basis of the CT data using the Mechanical Finder (MF) software (RCCM Inc.).

The analytical model consisted of the lower jaw, teeth, periodontal membranes, a correcting wire and brackets. The jaw was cut at the sagittal plane, and the left half was used as the model because it is bilaterally symmetric. The
lower jaw and teeth were constructed on the basis of the CT images. The implant anchor was not considered in the model. However, the position of the anchor was used to determine the direction of the force acting on the wire. The periodontal membranes between the bone of the lower jaw and the teeth were created by the expansion of the outer shape between the neck and apical parts of the teeth. The thickness of the membranes was 0.3 mm.

The brackets were modeled using computer-aided design (CAD) software (SolidWorks), imported from the SolidWorks software to the MF software as stereo lithography (STL) data, and set outside of the teeth using the MF software. The correcting wire of 0.3 mm diameter was modeled as follows. First, the model consisting of the lower jaw, teeth, periodontal membranes and brackets was imported into the SolidWorks software as STL data. Second, the wire was modeled by fitting it in the holes of the brackets using the SolidWorks software. Finally, the wire was imported in the MF software as STL data and placed in the correct position. The outer surface of the wire was in contact with the inner surface of the holes of the brackets.

Figures 1 and 2 show the analytical model, and the teeth, periodontal membranes, brackets and correcting wire constituting the analytical model, respectively. In Fig. 1, the numbers 4-7 denote the first premolar, second premolar, first molar and second molar, respectively. The brackets were fixed to teeth 4, 5 and 6.

Shell elements were used for the model of the periodontal membranes, and tetra elements were used for the other models. The size of the elements was varied for each model. The total numbers of shell and tetra elements were 257,650 and 20,170, respectively. The total number of nodes was 49,362.

Table 1 shows the material properties of the analytical model. The teeth, periodontal membranes, brackets and correcting wire were considered as homogeneous, and the lower jaw was considered as heterogeneous. The Young’s modulus for the jaw was calculated using Carter’s equation, which gives the relationship between the density of the human femur and the modulus, using the MF software. The density was obtained from the gray value data of the CT images. The material properties of the teeth and periodontal membranes were set on the basis of reference [23]. Stainless steel was used for the brackets and correcting wire.

### Table 1 Material properties

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower jaw</td>
<td>Carter</td>
<td>0.30</td>
<td>Automatic</td>
</tr>
<tr>
<td>Tooth</td>
<td>73.5</td>
<td>0.40</td>
<td>1.45×10³</td>
</tr>
<tr>
<td>Periodontal membrane</td>
<td>2.94×10³</td>
<td>0.49</td>
<td>1.20×10³</td>
</tr>
<tr>
<td>Bracket</td>
<td>196</td>
<td>0.34</td>
<td>8.03×10³</td>
</tr>
<tr>
<td>Wire</td>
<td>196</td>
<td>0.34</td>
<td>8.03×10³</td>
</tr>
</tbody>
</table>

3. Displacement Measurement Using Digital Image Correlation Technique

Figure 4 shows the experimental model, which consists of the lower jaw, teeth, periodontal membranes, the correcting wire, brackets and implant anchors. The lower jaw and teeth were made by pouring liquid epoxy resin into clay molds from standard molds. The jaw was cut at the sagittal plane, and the left half was used for modeling because of its bilateral symmetry, similarly to the analytical model discussed in section 2. The periodontal membranes were made by pouring liquid polyurethane between the lower jaw and the teeth. The Young’s moduli of the lower jaw, teeth and periodontal membrane were 2,931, 207 and 0.2 MPa, respectively. The shape of the model did not perfectly coincide with that of the analytical model because the latter was created on the basis of the CT data of a dried human skull.
Three teeth, the first and second premolars and the first molar, were connected by a correcting wire of 0.14 mm diameter through the brackets bonded on the teeth. The brackets and wire were fixed by a soft steel wire (fixing wire) of 0.2 mm diameter, as shown in Fig. 5. The material, shape and dimensions of the brackets and correcting wire were the same as those in the analytical model except for the diameter of the correcting wire. The experimental model was bonded on a steel plate (5 mm thick, 100 mm wide and 100 mm long), and the plate was fixed to a table for support using four bolts.

A force, $F$, of 5.88 N was applied by fixing a steel wire (loading wire) of 0.28 mm diameter to the brackets bonded on the first and second premolars, and by placing a weight on a saucer attached to the end of the loading wire, which passed through an implant anchor and a pulley. Load positions A and B are defined as in a previous report. The direction, $\theta$, of the force from the horizontal was set to 10º, 20º or 30º. These directions of the force were realized by passing the loading wire through the implant anchors, which were preliminarily twisted into the jaw at angles of $\theta=10º$, 20º and 30º, respectively, by adjusting the position of the implant anchors, as shown in Fig. 4.

Four images were taken before and after loading using two charge-coupled device (CCD) cameras. These images were used to obtain the displacement of the teeth using 3D digital image correlation software (Correlated Solutions Inc.).

4. Analytical and Experimental Results and Discussion

The movement of the molars of the lower jaw subjected to distal loads from an implant anchor, a correcting wire and brackets was investigated using the 3D FE method and compared with that of the lower jaw model obtained experimentally using the 3D digital image correlation technique. Figures 6 and 7 show the movements of three molars (the first and second premolars and first molar) for load position A and $\theta=10º$ and 30º, respectively, and Fig. 8 shows those for load position B and $\theta=10º$.

Figures 6(a) and (b) show the movements obtained analytically and experimentally, respectively. The analytical results indicated that the first premolar moved in...
the distal direction while tilting toward the buccal side, and
the second premolar moved in the distal direction with
counterclockwise rotation. The movement obtained
eperimentally was approximately consistent with that
obtained analytically. For the first molar, the analytical
results indicated movement in the distal direction with
slight counterclockwise rotation. Note that the rotation of
the first molar obtained experimentally was markedly
larger than that obtained analytically.

Figures 7(a) and (b) show the movements obtained
analytically and experimentally for load position A and
\( \theta = 30^\circ \), respectively. The analytical results indicated that
the first premolar moved in the distal direction while tilting
toward the buccal side with intrusion, and the second
premolar moved in the distal direction with
counterclockwise rotation. The movement obtained
experimentally was approximately consistent with that
obtained analytically. The movements of the first molar
obtained analytically and experimentally were similar to
those for load position A and \( \theta = 10^\circ \).

For load position A and \( \theta = 20^\circ \), not shown in this paper,
the tilt toward the buccal side and the intrusion of the first
and second premolars were larger than those for load
position A and \( \theta = 10^\circ \) and smaller than those for load
position A and \( \theta = 30^\circ \). The movements of the first molar
obtained analytically and experimentally were similar to
those for load position A and \( \theta = 10^\circ \) and 30\(^\circ \).

Figures 8(a) and (b) show the movements obtained
analytically and experimentally for load position B and
\( \theta = 10^\circ \), respectively. The analytical results indicated that
the first and second premolars moved in the distal direction
with a slight tilt toward the buccal side. The movement
obtained experimentally was approximately consistent with
that obtained analytically. For the first molar, the analytical
results indicate movement in the distal direction with slight
counterclockwise rotation. Similarly to the case shown in
Fig. 6, the rotation of the first molar obtained
experimentally was markedly larger than that obtained
analytically.

For load position B and \( \theta = 20^\circ \) and 30\(^\circ \), not shown in
this paper, the tilt toward the buccal side and the intrusion
of the first and second premolars were larger than those for
load position B and \( \theta = 10^\circ \). In particular, the movement
of the second premolar was considerable. The movements
of the first molar obtained analytically and experimentally
were similar to those for load position B and \( \theta = 10^\circ \).

For both load positions A and B, the tilt toward the
buccal side and the intrusion of the molars increased and
the movement in the distal direction decreased as \( \theta 
increased. The displacements of the molars for load
position A and \( \theta = 10^\circ \), 20\(^\circ \) and 30\(^\circ \) were smaller than those
for load position B. From these results, to move the molars
distally without inducing a large rotation, a large tilt
toward the buccal side or a large intrusion, load position B
and small \( \theta \) such as 10\(^\circ \) are desirable.

The movements of the first and second premolars
obtained analytically were in good agreement with those
obtained experimentally, whereas that of the first molar
differed markedly from the experimental result. This is
inferred to be mainly due to the discrepancy between the
shapes of the analytical and experimental models,
particularly the discrepancy of the shape of the correcting
wire joining the molars. The shape of the wire used for the
analysis was approximately linear because the alignment of

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the molars was approximately linear, as shown in Figs. 6-8. On the other hand, a circular wire was used for the experiment because the first molar tilted toward the lingual side, as shown in Figs. 6-8.

5. Conclusions
The movement of the molars of a lower jaw subjected to distal loads from an implant anchor, a correcting wire and brackets was investigated using a 3D FE method and compared with that of a lower jaw model obtained experimentally using a 3D digital image correlation technique. The analytical results for the movement were approximately consistent with the experimental results and indicated that the movement of the molars depended on the position and direction of the load.

References


